Dynamic Thermo-Elasto-Plasticity FE Analysis on Nano- and Femto-second Laser Shock Peenings for a Ferrite Material*

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Laser shock peening attracts increasing attention as one of techniques to improve fatigue life of materials and structures. The application of this technique generally induces a compressive residual stress field, modifies the geometrical shape and alters the material hardening. Nanosecond laser peening, which uses nanosecond laser pulse is necessary to be carried out in immersed water for the confinement of the plasma. On the other hand, femtosecond laser peening, which uses femtosecond laser pulse, can be carried out in the air because of its high laser intensity. However, both techniques proceed under a very high strain rate, making difficult to completely understand the whole peening process, therefore the best conditions for laser peening and the mechanism of creation of residual stress field have not been clarified well yet. In this study, finite element analyses are carried out to examine the residual stress field, displacement and distribution of equivalent plastic strain in order to examine the effect of laser peening on the material properties. Each technique was simulated by means of a single laser shot irradiating to the center of the specimen surface. We discuss the numerical results of the residual stress, displacement and equivalent plastic strain fields.

Key Words: Laser Shock Peening, Fatigue, Residual stress, Surface deformation, Material hardening

1. Introduction

Laser shock peening (LP) attracts increasing attention as one of the techniques to improve fatigue life of materials and structures1-2). The application of this technique to the Aluminum alloy generally induces a compressive residual stress field, modifies the geometrical shape and alters the material hardening3-6). Nanosecond LP, which uses nanosecond laser pulse, has to be carried out in immersed water for the confinement of the plasma. On the other hand, femtosecond LP using femtosecond laser pulse can be carried out in the air thanks to its high laser intensity2). However, both techniques proceed under too much high strain rate, making the whole the process difficult to observe and study, therefore, the best conditions for LP, together with the generation of the residual stress field have not been clarified well yet. In this work, finite element analyses of the peening processes for a Ferrite material are carried out in order to examine the residual stress, displacement and equivalent plastic strain fields and therefore better understand the effect of both nanosecond and femtosecond LPS.

2. Numerical simulation

Dynamic FE analyses were carried out by means of the commercial code ABAQUS/Explicit in order to analyze a single shot laser peening, with nano- and femto-second lasers. A schematic representation of the axi-symmetry model adopted in the laser peening simulation is shown in Fig. 1. 76,049 4-noded elements with reduced integration were adopted to analyze the peened area in a thermo-mechanical analysis. The material property is assumed to be within an elasto-perfectly-plasticity based on the previous study for Alminium alloy5,6) and the adopted mechanical properties are summarized in Table 1. Figure 2 shows the comparison between the yield stress and strain rate obtained in

![Fig. 1 Analyzed FE Model and boundary conditions](image)

| Table 1 Material properties |
|-----------------------------|
| Properties                  | Value  | Unit       |
| Static yield stress, $\sigma_y$ | 650    | MPa        |
| Density, $\rho$             | 7,830  | kg/m$^3$   |
| Elastic modulus, E          | 206,000| MPa        |
| Poisson’s ratio, $\nu$      | 0.3    |            |
| Conductivity, $\lambda$    | 53     | W/(m·K)    |
| Thermal coefficient, $\alpha$| 3.65x10$^{-3}$ |           |
| Specific heat, C            | 460    | J/(kg·K)   |
the numerical model and the one reported for an experimental test for a Fe. The relationship between the initial yield stress and strain rate is supposed to be the one reported in Eq. 1.

\[ \sigma_y (\text{MPa}) = \begin{cases} 2.3\dot{\varepsilon}^{0.4} & (5.0 \times 10^4 \leq \dot{\varepsilon}) \\ 900 + 55 \ln(\dot{\varepsilon})(1.0 \times 10^{-3} \leq \dot{\varepsilon} < 5.0 \times 10^4) \\ 650 & (\dot{\varepsilon} < 1.0 \times 10^{-3}) \end{cases} \] (1)

### Table 2 LP conditions

|                          | Pulse energy, Ep | Spot diameter, \( \phi \) | Laser intensity, \( I \) | Pulse duration, \( \tau \) | Pressure peak, \( t_{\text{peak}} \) | Max. pressure, \( P_{\text{max}} \) |
|--------------------------|------------------|-----------------------------|---------------------------|---------------------------|---------------------------------|---------------------------------|
| Nanosecond LP            | 1.5 J            | 1.5 mm                      | 3.5 GW/cm²                | 9 ns                      | 11 ns                           | 3.0 GPa                         |
| Femtosecond LP           | 0.06 J           | 0.5 mm                      | 2,500 GW/cm²              | 130 fs                    | 0.04 ns                         | 22 GPa                          |

**Fig. 2** Strain-rate dependent material property adopted in the FE analysis

**Fig. 3** Time history of the applied pressure

**Fig. 4** Temporal sequence of axial stress distribution (\( \sigma_{xx} \))
The experimental results revealed that a very high strain rate is induced in the process, and in the numerical simulation too the strain rate is always higher than $10^4$, limiting the definition of the yield stress with the first two equations of Eq. 1. A finer mesh was adopted in the neighborhood of the center of the surface (i.e. minimum element size of 6x0.4 μm). Infinite elements were adopted around the analyzed area as boundary conditions in order to avoid the influence of the reflected wave. The modeling of immersed water for confinement of the plasma is neglected as in the previous study since the shock load due to the ablation of water is directly applied as the surface pressure in this analysis. The time history for the applied pressure ($P_0(t)$) is shown in the Fig. 3. The wave length, diameter of the pressure spot and the maximum pressure for each pulse are summarized in Table 2. The pressure distribution induced by the laser pulse is supposed to be Eq. 2.

$$P(x,t) = P_{\text{max}} \times P_0(t) \sqrt{1 - x^2/r^2}$$

The time period for the simulation is 500 times the duration of the pressure pulse in order to avoid the influence of the accumulation of numerical errors.

3. Results and discussion

Figure 4 shows a temporal sequence of axial stress distribution at a fix time. In the case of nanosecond laser peening, the shock front is shown at 50ns, 100ns and 250ns, observing that in the last one a compressive residual stress field is created. However, it disappeared at 400ns. In the case of femtosecond laser peening, the compressive residual stress field is created after the passage of the stress wave.

The stress wave profiles at a fix times are shown in Fig. 5. In the nanosecond peening, the maximum stress component along the depth ($z$) are at maximum -3,000 MPa at 20ns. In the femtosecond LP case, the stress amplitudes are lower than -1,000MPa, with the exception of a peak at 0.112ns where the stress spikes at -17,900MPa. The estimated thermal increase induced by the plastic deformation is about 7K for the nanosecond LP case and 63K femtosecond LP. It should be noted that the thermal increase induced by the laser beam is neglected in this analysis.

The distribution of the equivalent plastic strain along the depth ($z$) is shown in Fig. 6. The predicted maximum equivalent plastic strain in the femtosecond LP exceeds the value of 2.5% at the center of peened area, which is more than 10 times nanosecond LP one (i.e. maximum value of 0.23%). Figure 7 reports the residual stress distribution in depth (i.e. along the $z$ component) at the center of the specimen for the nanosecond and femtosecond LP.
The maximum residual stress predicted for the nanosecond LP is about -200MPa whereas is about -1,200MPa in the femtosecond case. For both cases, the depth of compressive zone is about several tens of μm. Figure 8 shows the σxx distribution on the surface along the x direction. In the nanosecond LP, σxx tends to be almost negligible (i.e. around 200MPa), but it is more than -1,000MPa in the femtosecond LP case.

4. Conclusions

The present paper reported the results of numerical simulations for nano- and femto-second laser peening for Fe. The main conclusions can be summarized in the following three points:

1. In the nanosecond LP case, the maximum stress component predicted along the depth (i.e. z axis) is around -3,000 MPa at 20ns. On the other hand, the femtosecond LP induces a lower stress amplitude (around one third) with the exception of the stress in the very beginning of the analysis where at 0.112ns the peak of 5 time smaller than that of nanosecond LP is reached.

2. The maximum predicted equivalent plastic strain in the femtosecond LP exceeds the 2.5% magnitude at the center of peened area, which is more than 10 times the one induced in the nanosecond LP (0.23%).

3. In the nanosecond LP, σxx tends to be almost negligible (200MPa), whereas is more than -1,000MPa for femtosecond case.

It should be noted that the further research should be conducted to verify the analyzed results through the comparison with the experimental results on residual stress, surface deformation and material hardening.

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