LSP: Process Modeling

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LSP: Process modeling

• The simulation of the laser/material interaction.
• A “simple” plasma plume model.
• The mechanical effects.
• A reliable rheological model.
• Microstructural model.
The simulation of laser/material interaction and ablation

Model of the plasma plume

\[
\begin{align*}
\frac{dT_P}{dt} &= \frac{I_L(1-\lambda_P)(1+R_L\lambda_P)-I_P[1-R_P(1-\eta_P)(1-\lambda_P)]}{k_B N l \gamma(Z+1) \left( \frac{M^2}{2} + \frac{1}{\gamma(\gamma-1)} \right)} \\
\frac{dl}{dt} &= \sqrt{\frac{\gamma(Z+1)k_B T_P}{m}} \\
I_P &= 4\sigma \alpha_{abs} T_P^4 \\
\frac{d(Nl)}{dt} &= p_b e^{\frac{\Delta H \cdot m}{k_B}} \left( \frac{1}{T_b} - \frac{1}{T_S} \right) \frac{1}{\sqrt{2\pi m k_B T_S}}
\end{align*}
\]

- Plume temperature
- Plume length
- Plume emission
- Plume ion density

• Strong simplifications: plume in LTE, fluid dynamics is “0D”
A simple and effective dispersion parameter $\eta_p$

$$\lambda^P = e^{-\alpha_{abs} l}$$

The spreading of the plume, the radius of influence $\rho_p$.

The emitted energy calculus for each plasma plume element $\rho_i$, see Fig. 6.6.

The Laser Ablation Simulator is able to predict the ablated workpiece volume $\rho_P$ and by repeating this routine for all the surface elements where the plasma is generated the whole affected workpiece is solved as $\rho_P$.

Solution of the coupled system, and some results

The simulation of laser/material interaction
The simulation of laser/material interaction

Chapter 6

(a) $\eta_P = 0.5$

(b) $\eta_P = 0.7$

(c) $\eta_P = 0.9$

Fig. 6.8: Influence of intensity lost fraction $\eta_P$ on aluminum target. $I = 5 \cdot 10^{12}$ W/m$^2$, spot = 40 µm, $\tau = 100$ ns.

Fig. 6.12: Linear path simulation performed on aluminum with $\rho_p = 0$. $I = 2 \cdot 10^{13}$ W/m$^2$, spot = 20 µm, $\tau = 100$ ns, scan velocity = 200 mm/s.

Fig. 6.13: Linear path simulation performed on aluminum with $\rho_p = 10$. $I = 2 \cdot 10^{13}$ W/m$^2$, spot = 20 µm, $\tau = 100$ ns, scan velocity = 200 mm/s.
Recent development: the effects of plasma expansion speed

Wu, B., Work in Progress. Illinois Institute of Technology, Chicago
The “classic” model for LSP

\[ HEL = \left(1 + \frac{\lambda}{2\mu}\right) (\sigma_y - \sigma_0) \]

Hugoniot elastic limit

\[ \varepsilon_p(I_0) = \frac{-2HEL}{3\lambda + 2\mu} \left( \frac{P(I_0)}{HEL} - 1 \right) \]

Plastic deformation

\[ L = \frac{C_{el}C_{pl}\tau}{C_{el} - C_{pl}} \left( \frac{P - HEL}{2HEL} \right) \]

Deformed depth

\[ \sigma_{surf} = \sigma_0 - \left( \mu\varepsilon_p \frac{1 + \nu}{1 - \nu} + \sigma_0 \right) \left[ 1 - \frac{4L}{\pi r_0} (1 + \nu) \right] \]

Surface Residual Stress

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The limits of the “classic” model

- No hardening effects.
- No informations about tensile stress under the surface.
- No informations about microstructural effects.
Mechanical Threshold Stress Model

$$\sigma = (\tau_a + \tau_i + \tau_v + \tau_e) \frac{\mu}{\mu_0}$$

MTS: intrinsic component

\[ \sigma = (\tau_a + \tau_i + \tau_v + \tau_e) \frac{\mu}{\mu_0} \]

\[ \tau_i (\dot{\varepsilon}, T) = \sigma_i \left[ 1 - \left( \frac{k_b T}{g_0 i b^3 \mu} \ln \frac{\dot{\varepsilon}_0 i}{\dot{\varepsilon}} \right)^{\frac{1}{q_i}} \right] \frac{1}{p_i} \]
MTS: viscous drag component

\[ \sigma = \left( \tau_a + \tau_i + \tau_v + \tau_e \right) \frac{\mu}{\mu_0} \]

\[ \tau_v (\dot{\varepsilon}) = \frac{2B\dot{\varepsilon}}{\sqrt{3} \rho_m b^2} \]

Figure 4. Evolution of dislocation density as a function of plastic strain and temperature.
\[ \sigma = (\tau_a + \tau_i + \tau_v + \tau_e) \frac{\mu}{\mu_0} \]

\[ \tau_e (\varepsilon_p, \dot{\varepsilon}, T) = \sigma_{es} \left( \frac{\frac{2\theta_0 \varepsilon_p}{e^{\frac{\sigma_{es}}{2\theta_0 \varepsilon_p}} - 1}}{\frac{2\theta_0 \varepsilon_p}{e^{\frac{\sigma_{es}}{2\theta_0 \varepsilon_p}} + 1}} \right) \left[ 1 - \left( \frac{k_b T}{g_0 b^3 \mu} \ln \frac{\dot{\varepsilon}_{0e}}{\dot{\varepsilon}} \right) \frac{1}{q_e} \right] \frac{1}{\rho_e} \]
MTS: shear modulus

\[ \sigma = (\tau_a + \tau_i + \tau_v + \tau_e) \frac{\mu}{\mu_0} \]

\[ \mu(\rho, T) = \frac{1}{1 + e^{-\frac{(\xi+1)(T_m-T)}{\xi T_m (\xi+1)-\xi T}}} \left\{ \mu_0 + p \frac{\partial \mu}{\partial p} \left( \frac{a_1}{\eta^3} + \frac{a_2}{\eta^3} + \frac{a_3}{\eta} \right) \right\} \left( 1 - \frac{T}{T_m} \right) + \frac{\rho}{cm} k_b T \]
MTS: flow stress examples on C40

strain rate = $10^8$ s$^{-1}$
Simulation results: 1.5 GW/cm$^2$

- Laser pulse: 8 ns, 1.5 GW/cm$^2$; 2 J.
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- Plasma vapour pressure
Simulation results: 1.5 GW/cm²

- Plasma vapour pressure
Simulation results: 1.5 GW/cm$^2$

- Flow stress, MTS model on C40 (AISI 1040)
Simulation results: 1.5 GW/cm$^2$

- Flow stress, MTS model on C40 (AISI 1040)
Simulation results: 1.5 GW/cm²

- Hugoniot elastic limit
Simulation results: 1.5 GW/cm$^2$

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- Surface residual stress
Simulation results: 1.5 GW/cm²

- Surface residual stress
Simulation results: 1.5 GW/cm$^2$

- Example of triangular pulse
Simulation results: 1.5 GW/cm²

• “Chirped” pulse
Simulation results: 1.5 GW/cm²

- “Chirped” pulse, significantly increase the effects on the material
Microstructural effects: high nucleation density, grain refinement


Table 4

<table>
<thead>
<tr>
<th>Contact depth</th>
<th>Elastic modulus</th>
</tr>
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<tbody>
<tr>
<td>H</td>
<td>E</td>
</tr>
<tr>
<td>0.535</td>
<td>196.07</td>
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<tr>
<td>0.718</td>
<td>150.51</td>
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<tr>
<td>0.846</td>
<td>114.20</td>
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</tbody>
</table>

Fig. 4.
Evaluation of the nucleation site density

\[ N_0 (I_0, T) = \frac{1}{2} \rho_t (I_0, T)^{\frac{3}{2}} \]

Available nucleation site density

\[ \rho_t = \left( \frac{\sigma_d}{M \gamma \mu b} \right)^2 = \left( \frac{\sigma - \sigma_0}{M \gamma \mu b} \right)^2 \]

Dislocation density
Numerical results on AISI 1040, $T = 500 \text{ K}$; $I = 1.5 \text{ GW/cm}^2$; $\tau = 8 \text{ ns.}$

- Surface strain.
- Plastic deformation depth.
- Residual stress on the surface.
- Nucleation site density.
Thanks!
Thank you for your attention

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