Simulation of stress waves induced by laser shock in an elastic plastic layered material

GDR MePhy 2022

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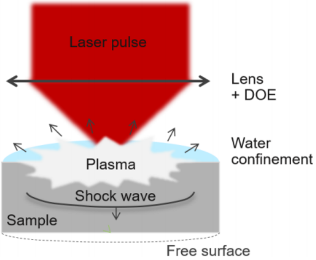
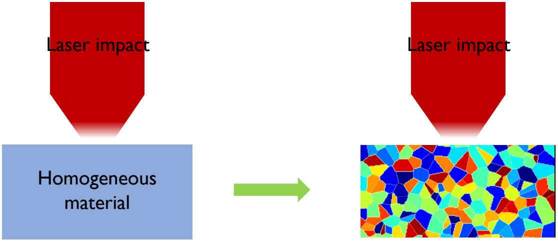
Laser **S**hock **P**eening: generates residual stresses by laser impact (illustration: [Scius Bertrand et al., 2020]).
Compressive residual stresses improve the fatigue resistance of materials [Peyre et al., 1996].



Laser spot diameter: $\sim$ mm, **pressure**: $\sim$ GPa, **pulse duration**: $\sim$ 10 ns, **strain rate**: $\sim 10^6$ s^{-1}.
To properly study and implement the LSP process, precise numerical models leading to accurate results are necessary.

Usual modeling approaches for LSP: **isotropic homogeneous** materials models with a **strain rate-dependent** plastic behavior.



Standard isotropic modeling

Microstructure modeling ?

Current modeling strategies: no influence of the **microstructure** $\rightarrow$ irrelevant for **very small spot sizes** ($\approx 10\ \mu m$ for μLSP).

Problematic: what is the influence of a heterogeneous model on the elasto-plastic stress wave propagation ?

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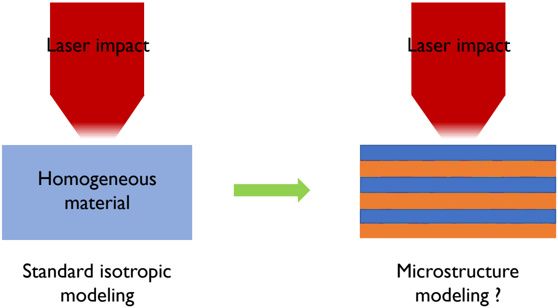

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Stress wave propagation modeling: **hyperbolic equation**.

Starting from:

$$\begin{cases} \operatorname{div}(\boldsymbol{\sigma}) + \boldsymbol{f} = \rho(x)\dfrac{\partial \boldsymbol{v}}{\partial t} & \text{dynamic equilibrium} \\ \boldsymbol{\sigma} = \mathbb{C}(x) : (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}_p) & \text{Hooke's law} \end{cases}, \qquad (1)$$

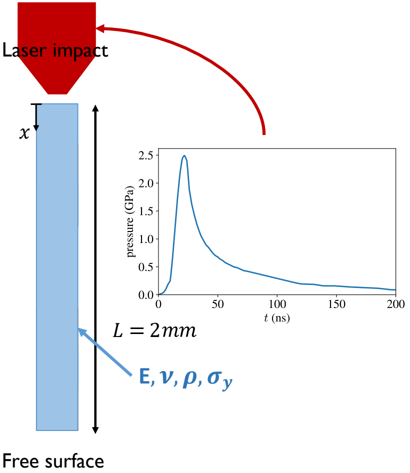
For small displacements and **uniaxial** strains, it becomes:

1D hyperbolic equation

$$\begin{pmatrix} \sigma_{11} \\ v_1 \end{pmatrix}_{/t} + \begin{pmatrix} 0 & C_{1111}(x) \\ \dfrac{1}{\rho(x)} & 0 \end{pmatrix} \begin{pmatrix} \sigma_{11} \\ v_1 \end{pmatrix}_{/x} = 0 \qquad (2)$$

Uniaxial strains: state of the material along the **center of the impact** [Ballard, 1991].

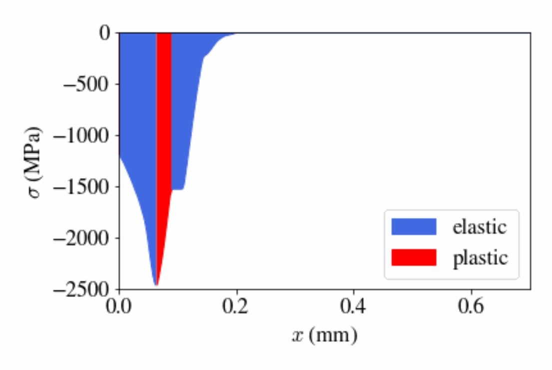
Illustrative example: **homogeneous** propagation.



- Material model: isotropic, with **elastic perfectly plastic** behavior.
- Resolution with **finite differences** explicit time integration.
- Numerical scheme: **Godunov with high resolution** [Leveque, 2002].

Illustrative example: **homogeneous** case.

Steel-like material: $E = 210$ GPa, $\nu = 0.3$, $\rho = 7800$ kg/m^3, $\sigma_y = 870$ MPa.



- The transition from elasticity to plasticity is marked by a plateau.
- Elastic waves travel faster than plastic waves.

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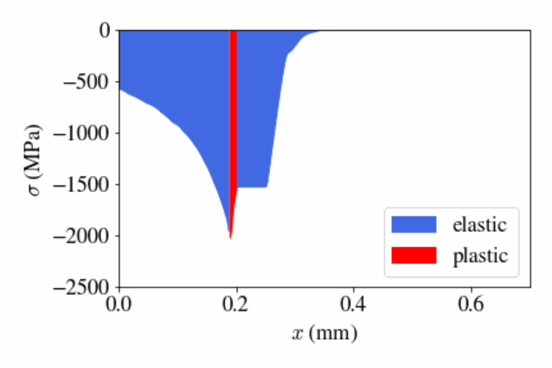

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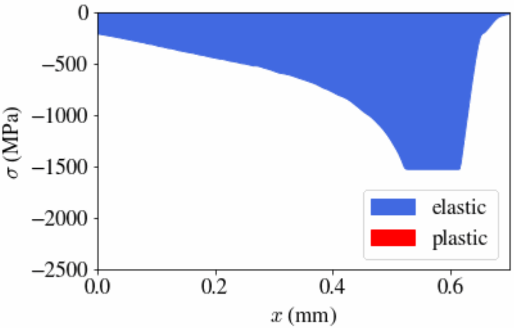

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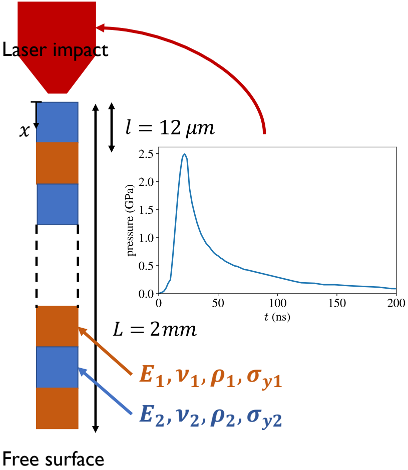
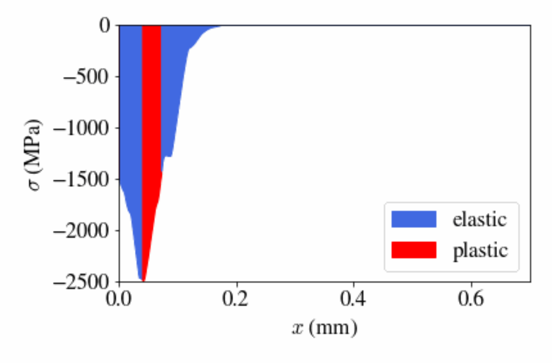
Heterogeneous material modeling: laminate material.



- Laminate composed of **2 phases** with **periodic** pattern.
- phases locally **isotropic** and **elastic perfectly plastic** behavior.
- Phases with **perfect** interfaces.

Current model: **heterogeneous** case.
Variations for elastic parameters only : $E_1 = 216$ GPa, $\nu_1 = 0.34$, $E_2 = 202$ GPa, $\nu_2 = 0.25$ ($\rho_1 = \rho_2 = 7800$ kg/m^3, $\sigma_{y1} = \sigma_{y2} = 870$ MPa).



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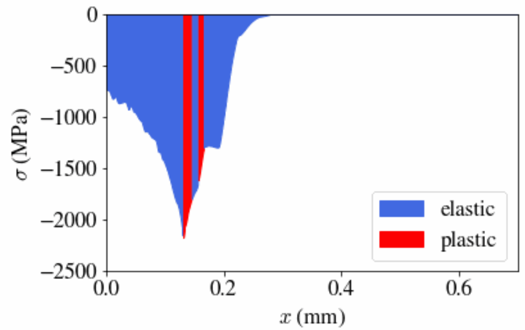

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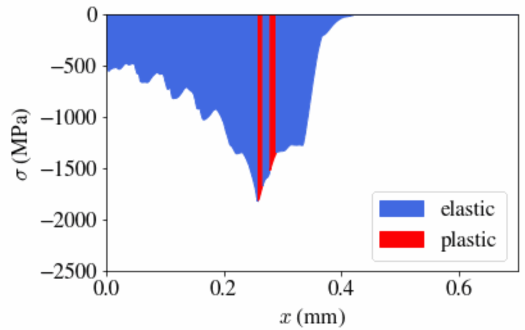

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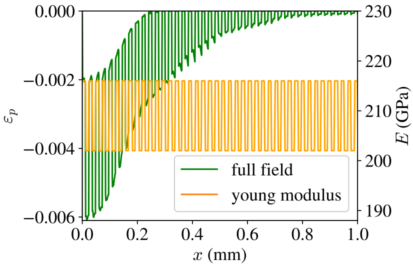
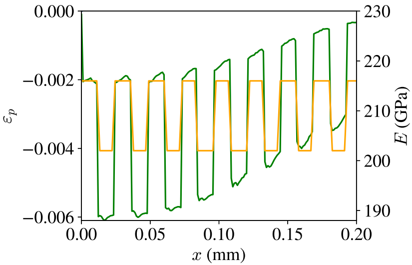
Results: plastic strain spatial profile.
Heterogeneous plastic strains are critical for **residual stresses**.

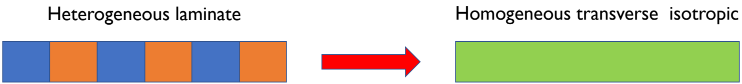




- Plastic strains are discontinuous.
- **Problem:** this modeling requires a fine mesh → long computation times (here ∼ 30 min for 1600 elements).

Problem: how to reduce computation times while achieving similar results?
Solution: find the most equivalent elastic-plastic homogeneous material.

1^{st} **step**: find the equivalent elastic behavior for the laminate.

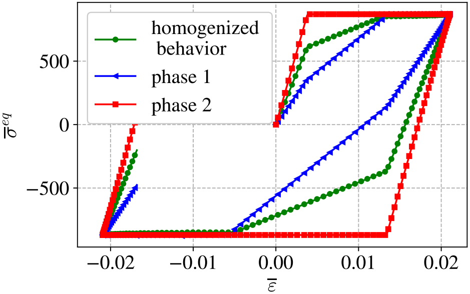


Find $\widetilde{\mathbb{C}}$ such that $\overline{\sigma} = \widetilde{\mathbb{C}} : \widetilde{\varepsilon}_e = \langle \mathbb{C} : \varepsilon_e \rangle$.

Validity: the typical length of the layers must be small before the wavelength of the stress wave [Capdeville et al., 2010].

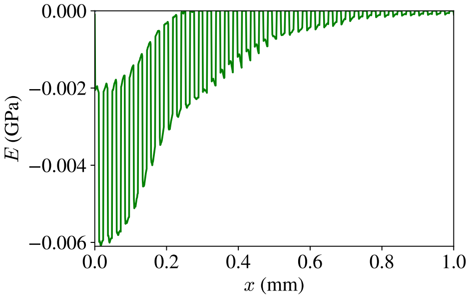
Here: $\sim$ 10 layers within the stress wave.

2nd step: find the equivalent **plastic** behavior.
From local equations, compute the relation between $\dot{\overline{\boldsymbol{\sigma}}}$ and $\dot{\overline{\varepsilon}}$ depending on how many phases plastify (illustrated below).



This model is able to predict the **effective elastic-plastic behavior**, and also the **localized** plastic strain.

Numerical results of the homogenized model: **localized plastic strains**



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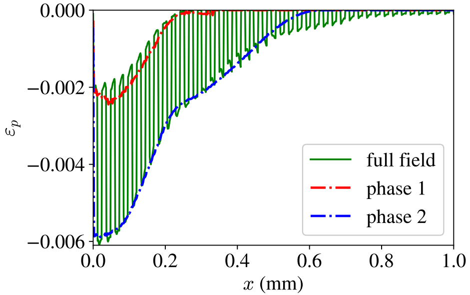

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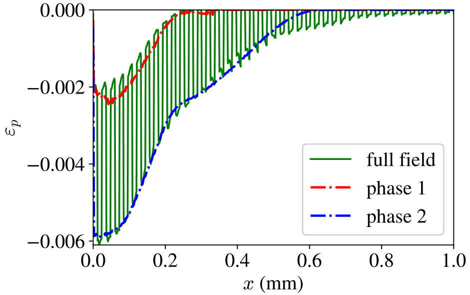


- The local plastic strains can be computed.
- Stress wave oscillations prevent a total match.
- Here computations are ≈ 4-5 times shorter, for 600 elements.

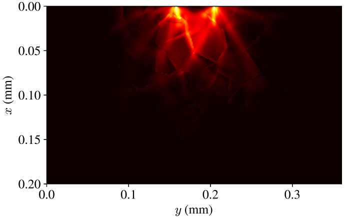
Conclusions:

- The stress wave propagation in an elastic plastic heterogeneous material was studied.
- First results show an influence on stress wave propagation and plastic strains profiles.
- The influence of the heterogeneous model was modeled by a homogenized behavior.
- The developments can be found in [Lapostolle et al., 2022, IJSS].

Outlooks and limitations:

- The residual stresses can be computed via analytic models.
- Experimental validation is difficult.
- Current works : 2D propagation in monocrystals and polycrystals.

plastic strain field in polycrystal:



Thank you for your attention !

Feel free to ask any questions

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Notations

l : size of smallest heterogeneity pattern

L : length of the spatial domain

x : spatial coordinate

$\boldsymbol{\sigma}$: Cauchy stress tensor

$\boldsymbol{f}$: body forces

ρ : density

$\boldsymbol{v}$: velocity vector

$\mathbb{C}$: stiffness tensor

ε : total strain tensor

ε_p : plastic strain tensor

$_{/x}$: derivative with respect to variable x

E : Young's modulus

ν : Poisson ratio