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The Numerical Challenges in Multiphysical Modeling of Laser Welding with ALE

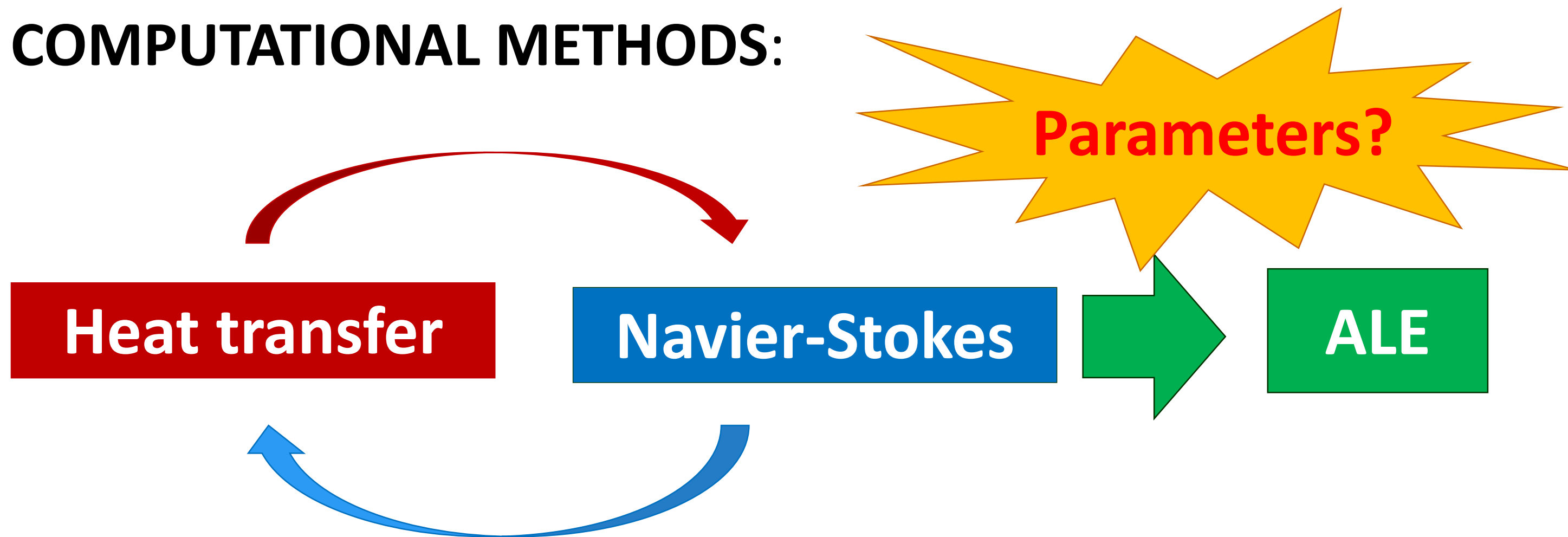
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INTRODUCTION: The present work summarizes the numerical challenges in creation and validation of free-surface models using ALE moving mesh coupled with heat transfer equation and Navier-Stokes fluid flow. The influence of a set of numerical parameters as well as physical hypotheses on the dynamics of the keyhole and the characteristics of the melt formed in titanium alloy Ti-6Al-4V is analyzed.

COMPUTATIONAL METHODS:



Heat transfer

- time-dependent
- standalone laser pulse
- T-dependent absorption coefficient

$$\rho c_p^{eq} \left(\frac{\partial T}{\partial t} + \vec{U} \cdot \vec{\nabla} T \right) = \vec{\nabla} \cdot (\lambda \vec{\nabla} T)$$

$$c_p^{eq} = c_p + D_m L_m \quad D_m = \frac{e^{-\frac{(T-T_m)^2}{\Delta T}}}{\sqrt{\pi \Delta T^2}}$$

$$q_L = \frac{P_L A}{\pi r_0^2} e^{-\left(\frac{x^2+y^2}{r_0^2}\right)} \cdot (t < t_{pulse})$$

$$A = A_{solid} + (A_{liquid} - A_{solid}) \cdot f_{lc} 2hs(T - T_m, \Delta T),$$

$$A_{liquid} = A_{surf} + (A_{kh} - A_{surf}) \cdot f_{lc} 2hs(T - T_v, \Delta T),$$

Navier-Stokes

Newtonian liquid
Mean viscosity in solid phase
Inconsistent stabilization

$$\vec{\nabla} \cdot \vec{U} = 0$$

$$\rho \left[\frac{\partial \vec{U}}{\partial t} + (\vec{U} \cdot \vec{\nabla}) \vec{U} \right] = \vec{\nabla} \cdot \left[-pI + \eta(T) \left(\vec{U} \cdot \vec{\nabla} + (\vec{U} \cdot \vec{\nabla}) \right) \right] + \vec{F}$$

$$\eta(T) = \eta_{solid} + (\eta_{liquid} - \eta_{solid}) f_{lc} 2hs(T - T_m, \Delta T).$$

- natural convection (Boussinesq approximation),
- surface tension force / Marangoni convection
- recoil pressure in the keyhole

$$p_r = \frac{(1+\beta)}{2} \cdot a \cdot e^{-\frac{b}{T+c}}$$

ALE

- Hyperelastic smoothing is better
- Deformation driven by velocity field

Parametric studies :

- ALE smoothing methods
- Numerical stabilization of N-S equation
- **Solid** and liquid viscosity
- **Adsorption in the keyhole** A_{KH}
- **Condensation coefficient** β
- Incompressible VS weakly compressible N-S

RESULTS: Optimal parameters allow to reproduce the whole lifetime of the keyhole during pulsed welding of Ti6Al4V alloy (temperature field + velocity field).

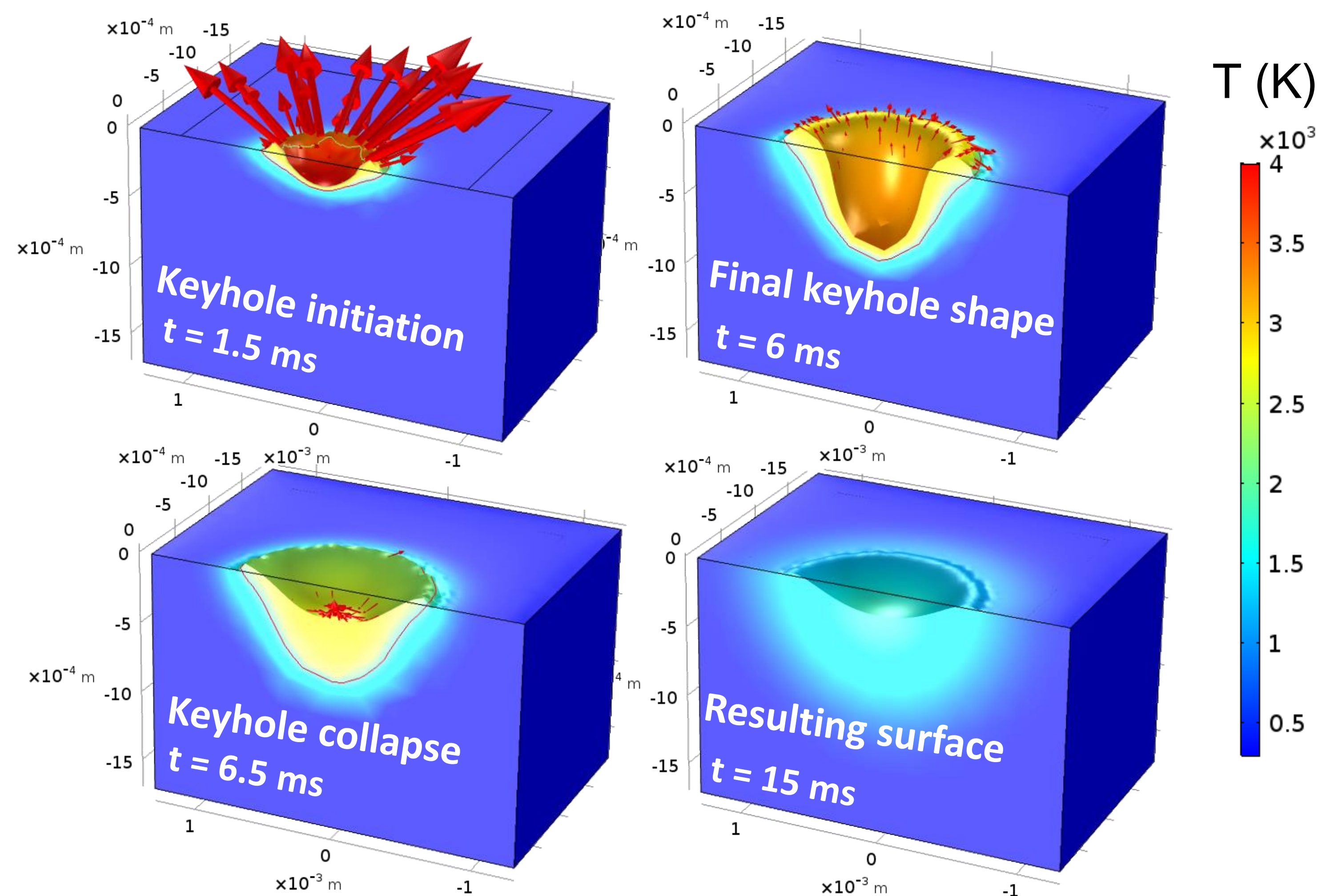


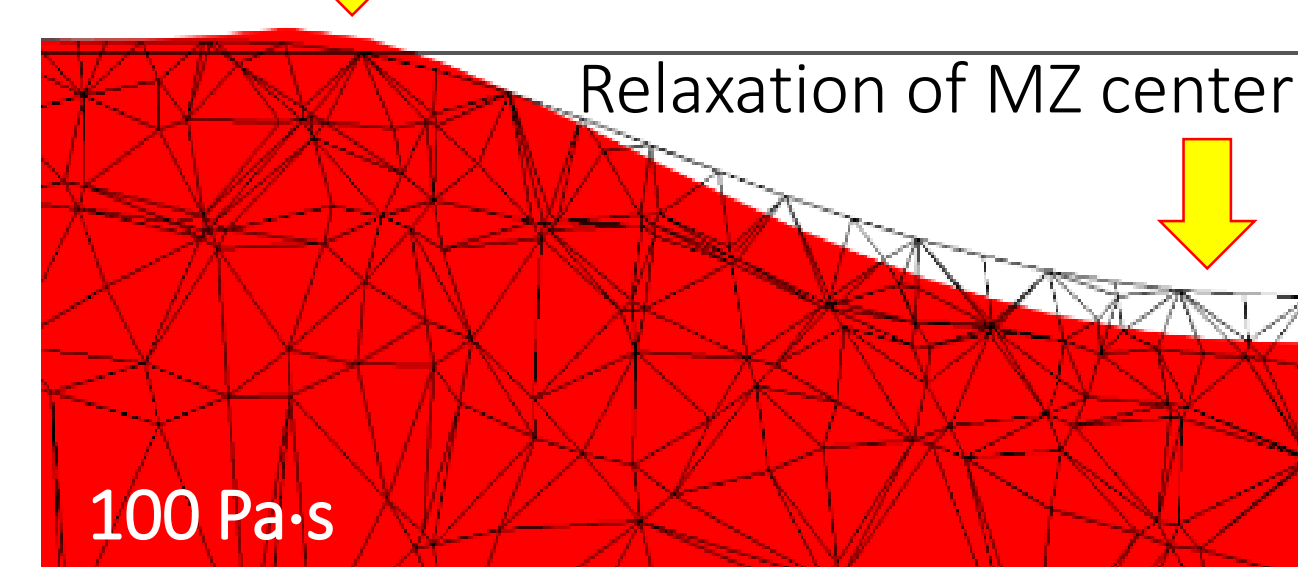
Figure 1. Nd:YAG laser pulse of 6 ms, 1.5 kW, $\phi = 560 \mu\text{m}$, $\eta_{solid} = 200 \text{ Pa}\cdot\text{s}$.

Influence of critical parameters:

Avoid low solid viscosity

- Parasite velocities in solid
- Less profound keyhole
- Unphysical relaxation of solid

Relaxation of solidified ring



Red profile - end of solidification
Wireframe - end of cooling

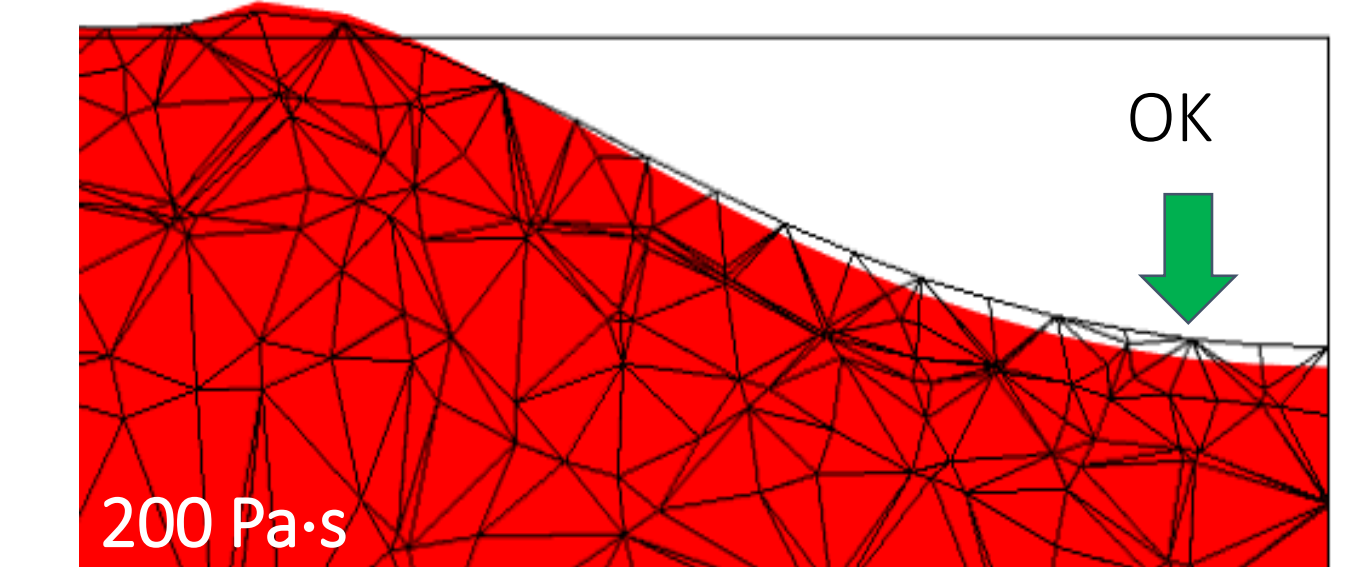


Figure 2. Unphysical relaxation of solidified weld between the end of solidification and the end of cooling for different solid viscosities.

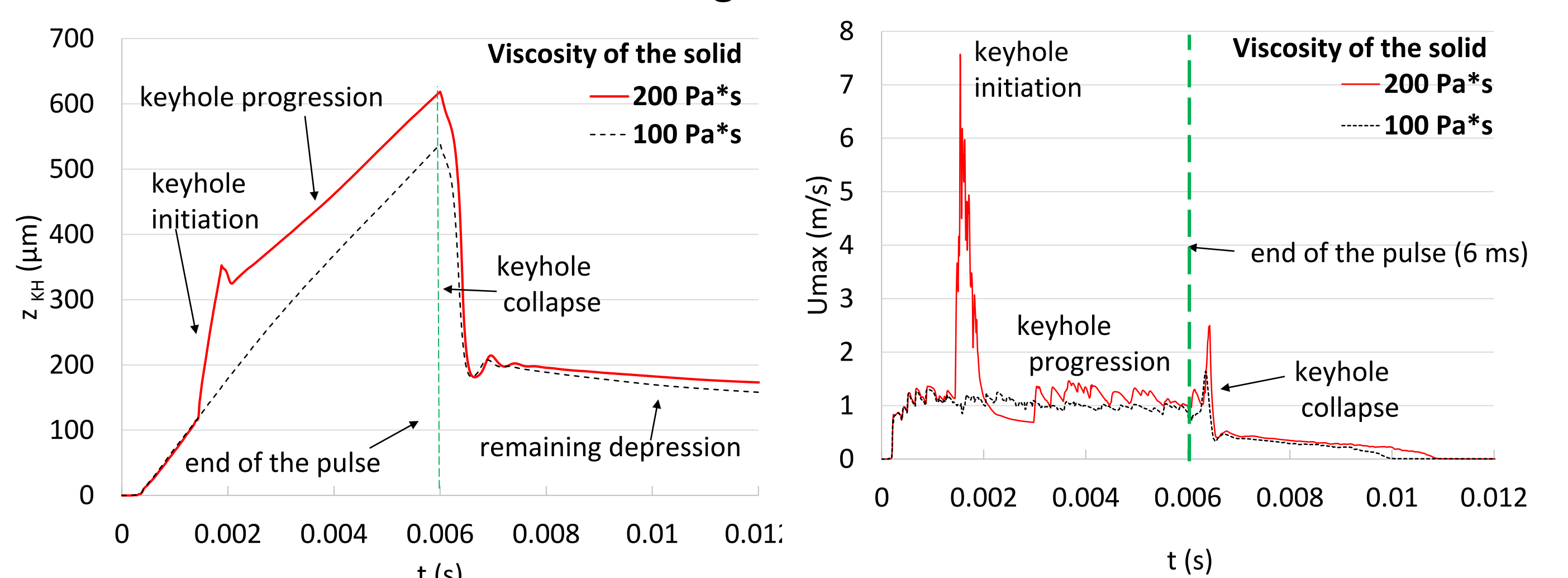


Figure 3. The influence of solid viscosity on the evolution of maximal temperature, melt velocity and keyhole depth for standalone Nd:YAG laser pulse on Ti-6Al-4V plate (6 ms, 1.5 kW, $\phi = 560 \mu\text{m}$).

$A_{KH} > 0.8$

$\beta > 0.5$

Convergence problems

Important undershoots of pressure and stress accumulation around the impact zone

CONCLUSIONS:

- Convergence problems associated with too important deformation of free surface (**remeshing?**)
- Keyhole depth sensitive to : solid and liquid viscosity, keyhole adsorption coefficient and condensation coefficient
- Acceptable mass conservation