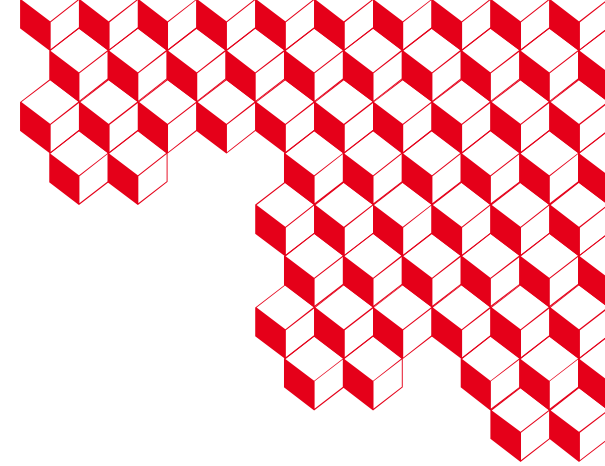




Numerical Investigation of Oxidation and Assist Gas Flow in Laser Cutting

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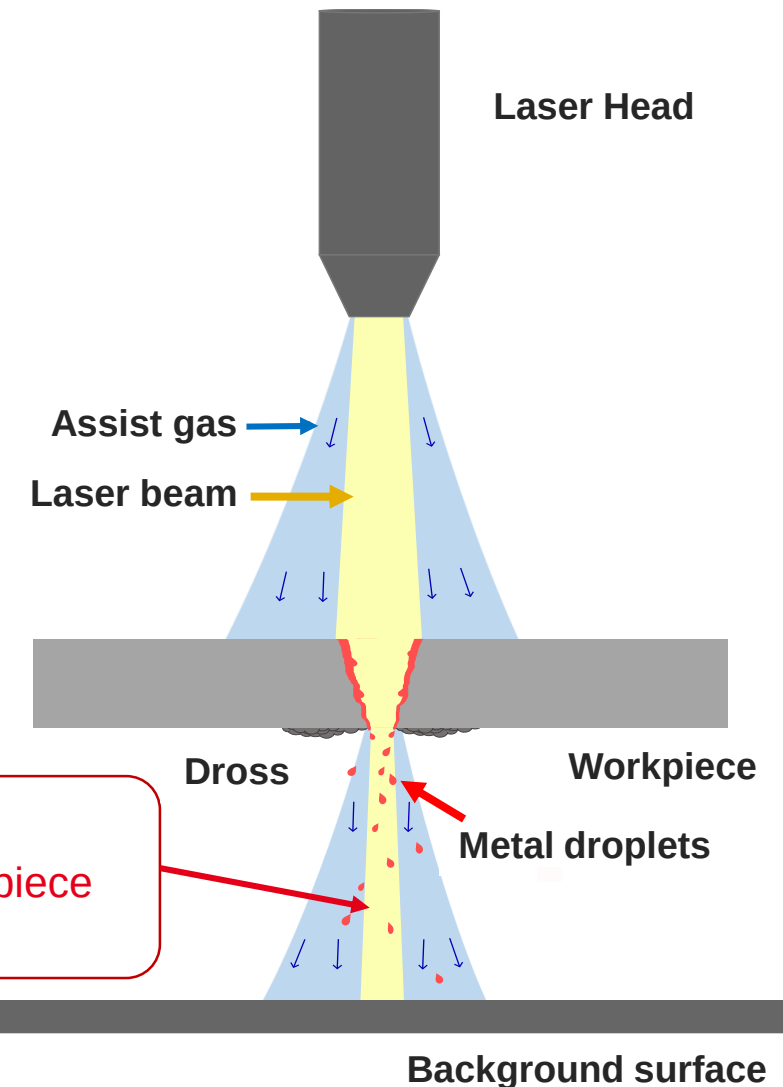
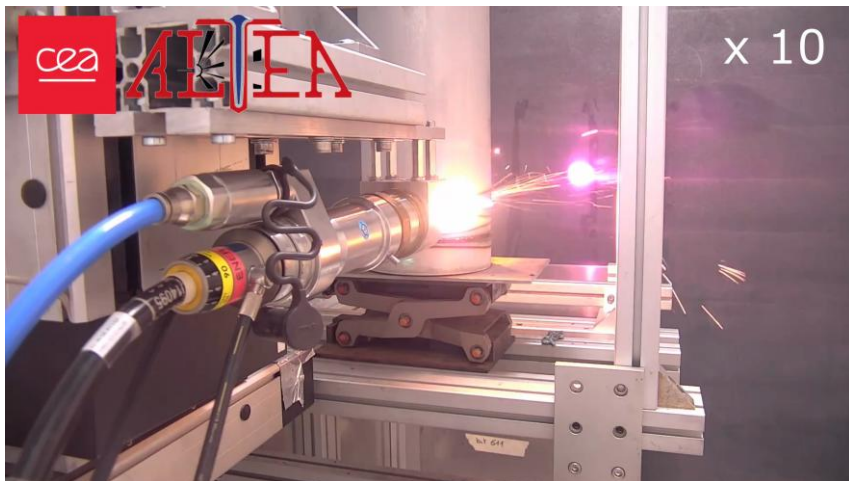
CONTEXT

Laser Cutting :

- Widely used in the manufacturing industry
- A laser beam heats and melts a material & an assist gas expels the molten material

Application to Nuclear Decommissioning :

- A promising technology for **dismantling nuclear facilities & power reactors**
- Cuts **thick metallic structures** in **hazardous environments**, regardless of surface quality



Residual laser energy:

- propagates beyond the workpiece
- may damage background

CONTEXT

Ph.D dissertation by R. Meillour (2025) [1]

Objective: Estimation of residual laser energy based on operating parameters

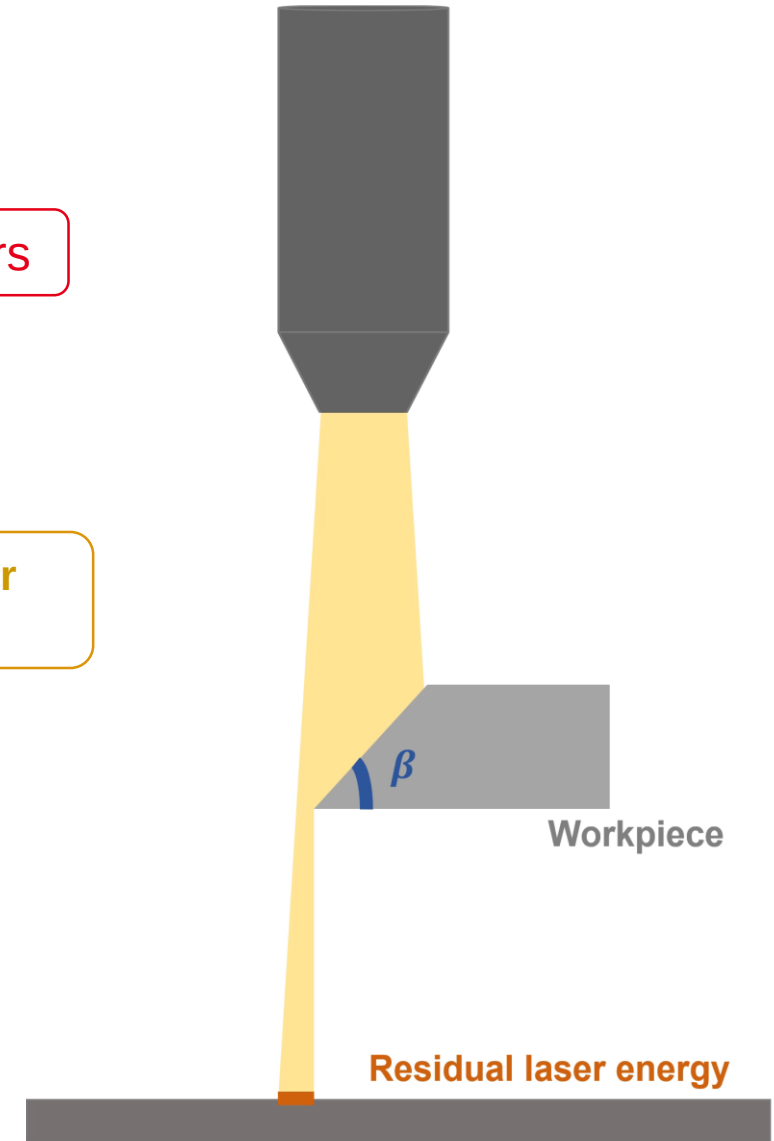
Operating parameters:

- Laser power (P_{laser})
- Cutting speed (v_d)
- Sample thickness
- Assist gas flow rate ($q_{v,gas}$)
- Assist gas type (inert or air)

Cut front angle
(β)

Residual laser
energy

Development of a thermohydrodynamic model in COMSOL Multiphysics® to determine cut front profile [2]

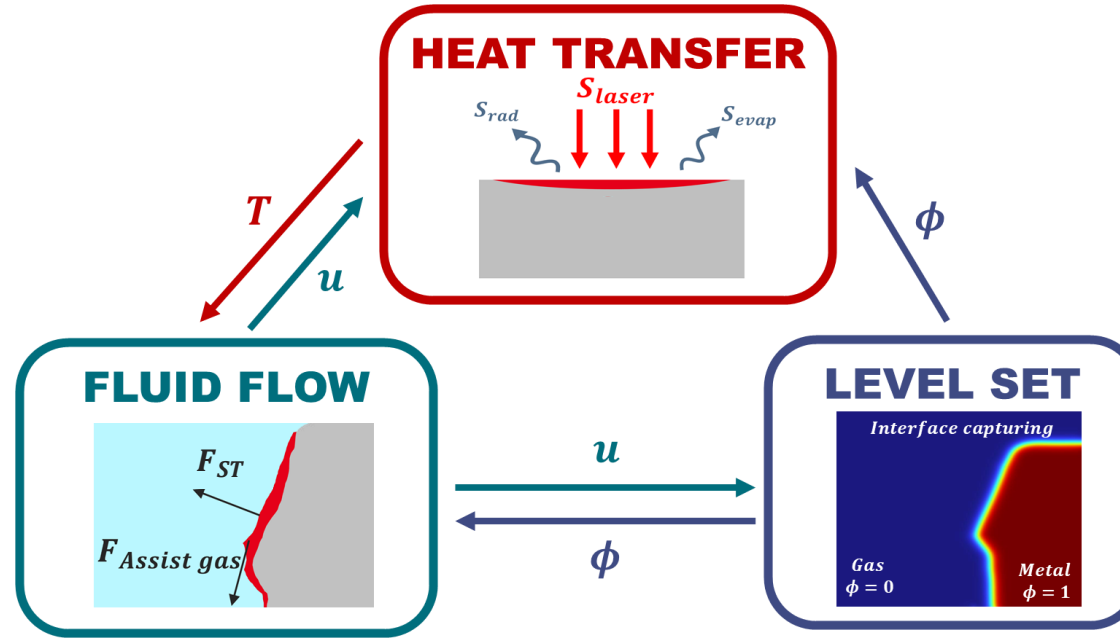


[1] R. Meillour, Ph.D. dissertation, Université de Bretagne Sud, 2025.

[2] R. Meillour et al., COMSOL Conference, 2023

LASER CUTTING MODEL

Ph.D dissertation by R. Meillour (2025) [1]



HEAT TRANSFER

$$\rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) = \nabla \cdot (\lambda \nabla T) + [S_{laser} - S_{evap} - S_{rad}] \delta(\phi)$$

FLUID FLOW

$$\begin{aligned} \nabla \cdot \mathbf{u} &= 0 \\ \rho \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right) &= \nabla \cdot [-p\mathbf{I} + \mu(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] + [F_{ST} + F_{Assist}] \delta(\phi) \end{aligned}$$

LEVEL SET

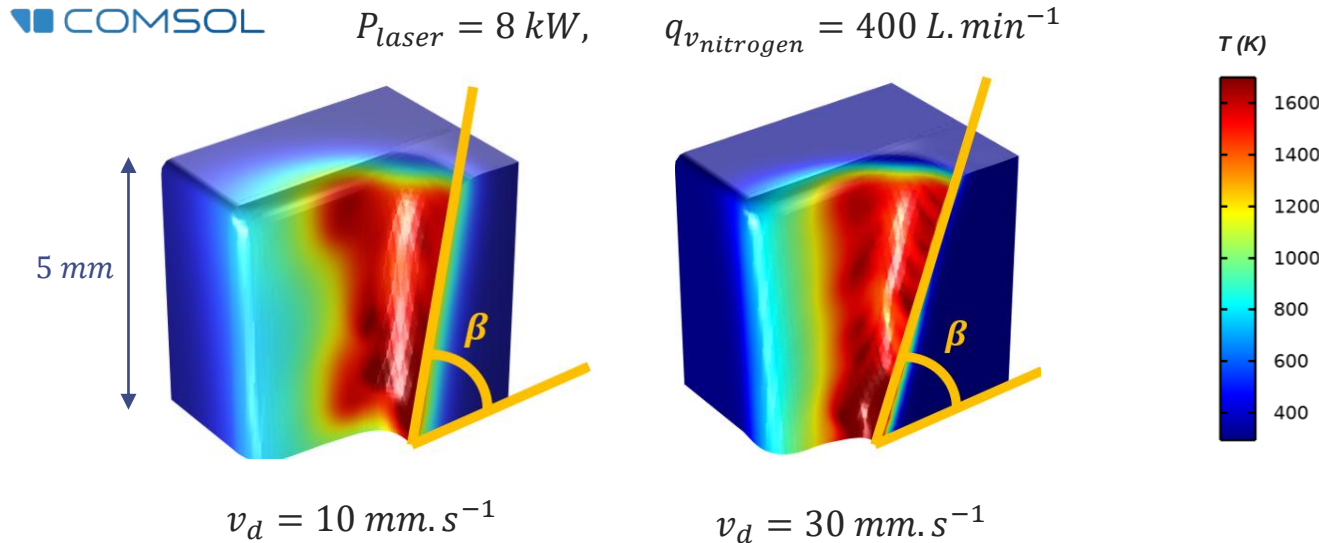
$$\begin{aligned} \frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi \\ = \gamma_{LS} \nabla \cdot \left[\epsilon_{LS} \nabla \phi - \phi(1 - \phi) \frac{\nabla \phi}{|\nabla \phi|} \right] \end{aligned}$$

[1] R. Meillour, Ph.D. dissertation, Université de Bretagne Sud, 2025.

LASER CUTTING MODEL

Ph.D dissertation by R. Meillour (2025) [1]

Numerical results:



Main findings:

- Dependence of **cut front angle** on operating parameters
- Cutting in **air** leads to **larger cut front angles** due to **oxidation** ($\beta_{air} > \beta_{N_2}$)

Experimental results:

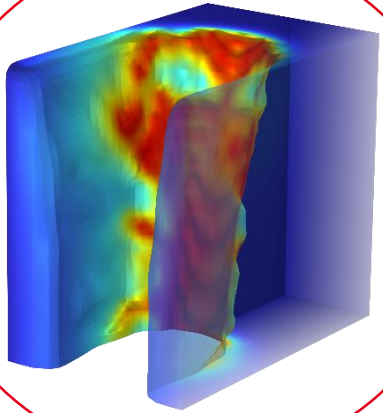
$$v_d = 5 \text{ mm.s}^{-1}, q_v = 100 \text{ L.min}^{-1}$$

Limitations:

- Oxidation not considered** in numerical model
- Assist gas represented through a **dynamic pressure and friction force**

[1] R. Meillour, Ph.D. dissertation, Université de Bretagne Sud, 2025.

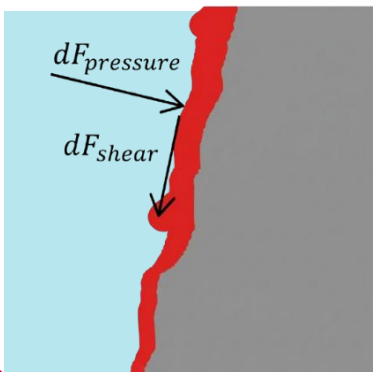
RESEARCH AIMS



Oxidation Effects

Addition of a **heat source** in the thermohydrodynamic model representing the **exothermic oxidation** reaction

Physics interfaces: Two-Phase Flow (Level Set) + Heat Transfer in Fluids

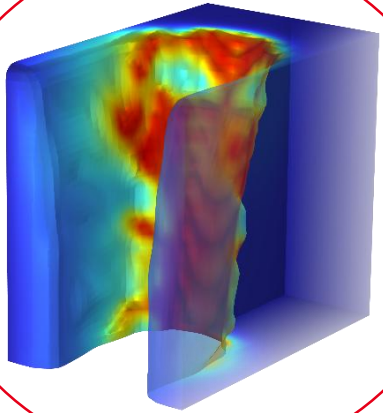


Assist Gas Effects

Modeling the assist gas using **compressible Reynolds-Averaged Navier Stokes (RANS)** equations to estimate forces at metal-gas interface

Physics interface: High-Mach Number Flow

RESEARCH AIMS



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OXIDATION OF 304L STAINLESS STEEL

Oxidation mechanism of 304L steel (72% Fe + 18% Cr) :

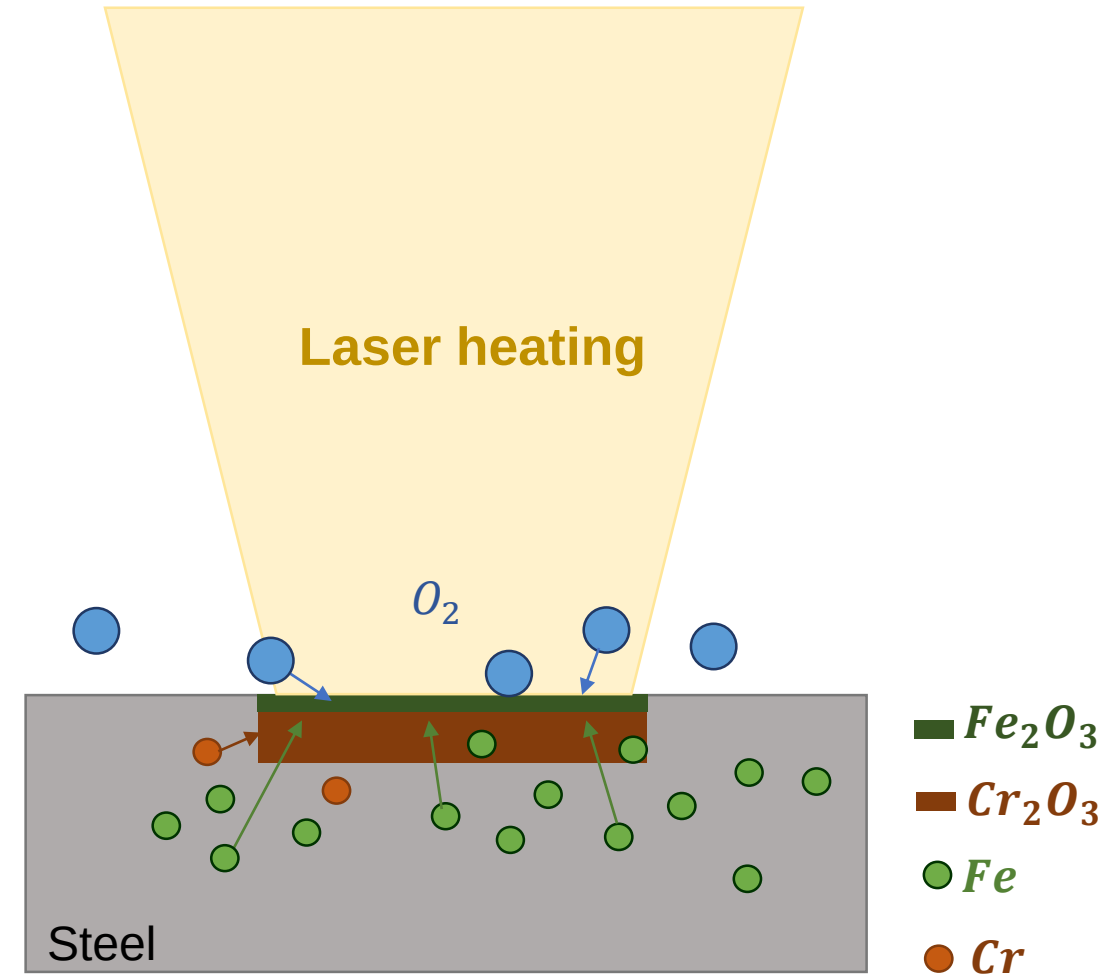
- $2Cr + \frac{3}{2}O_2 \rightarrow Cr_2O_3 + \Delta H_{f,1}^0$ $\Delta H_{f,1}^0 = -1163.67kJ/mol$
- Cr_2O_3 forms a **protective barrier** → reducing the oxidation rate
- $2Fe + \frac{3}{2}O_2 \rightarrow Fe_2O_3 + \Delta H_{f,2}^0$ $\Delta H_{f,2}^0 = -826.7kJ/mol$

In laser cutting:

- Oxidation can contribute up to 60% of total heat input * [4]

* Reported for pure O_2 cutting at 900W

[4] J. Powell et al., *Journal of Laser Applications*, 5, pp. 25–31, 1993.



OXIDATION OF 304L STAINLESS STEEL

Modeling the oxidation heat:

- Chemical transport equations
- Experimentally calibrated expressions [5]

Proposed oxidation heat source:

$$S_{oxi} = \underbrace{\rho_m v_d \sin \beta}_{\text{material removal}} \sum_{i=1}^{n^{\circ} \text{ of elements}} \left(\underbrace{f_i}_{\text{element frac}} \cdot \underbrace{\alpha_{ox}}_{\text{oxidized frac}} \cdot \underbrace{\Delta H_f^0}_{\text{enthalpy}} \right)$$

Added in:

$$\rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) = \nabla \cdot (\lambda \nabla T) + \underbrace{\left[S_{laser} - S_{evap} - S_{rad} + S_{oxi} \cdot H(T - T_s, \Delta T) \right]}_{\text{Volumetric heat source}} \delta(\phi)$$

[5] G. K. L. Ng et al., International Journal of Heat and Mass Transfer, 49, pp. 1358–1374, 2006.

OXIDATION OF 304L STAINLESS STEEL

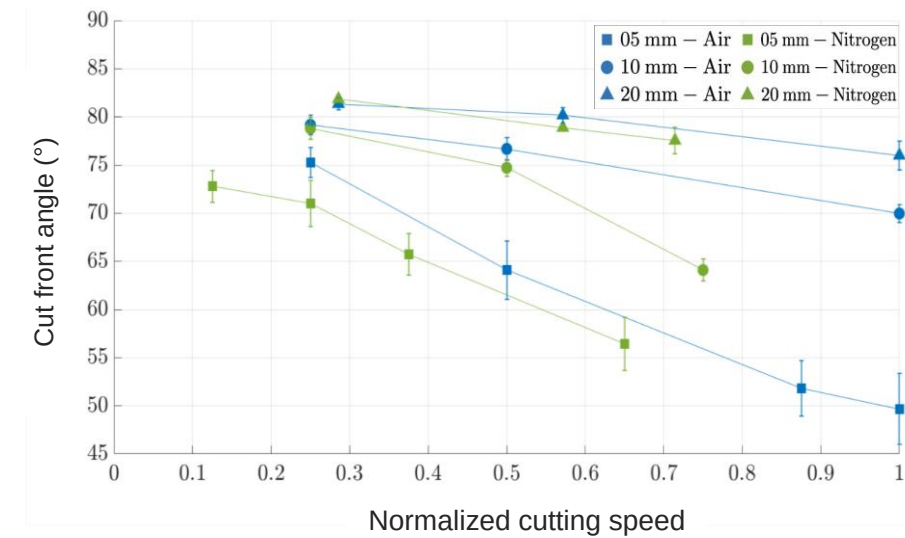
Results:

$$P_{laser} = 8kW, \quad th = 5mm, \quad v_d = 30mm.s^{-1}, \quad q_v = 100L.min^{-1}$$

$$d_{mesh} = 100\mu m, \quad \Delta t = 20\mu s$$

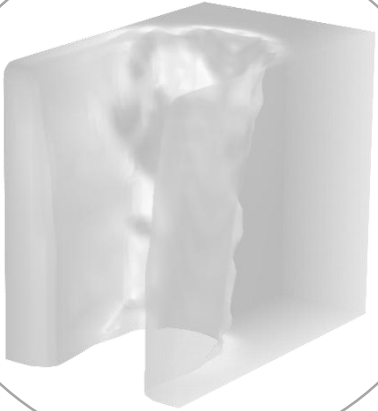
✓ $\beta_{ox} > \beta_{inert}$

Consistent with experiments in [1]



[1] R. Meillour, Ph.D. dissertation, Université de Bretagne Sud, 2025.

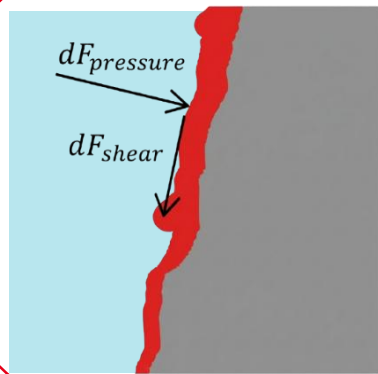
RESEARCH AIMS



Oxidation Effects

Addition of a heat source in the thermohydrodynamic model representing the exothermic oxidation reaction

Physics interfaces: Two-Phase Flow (Level Set) + Heat Transfer in Fluids



Assist Gas Effects

Modeling the assist gas using compressible Reynolds-Averaged Navier Stokes (RANS) equations to estimate forces at metal-gas interface

Physics interface: High-Mach Number Flow

ASSIST GAS EFFECTS

Assist gas effects previously represented via [6]:

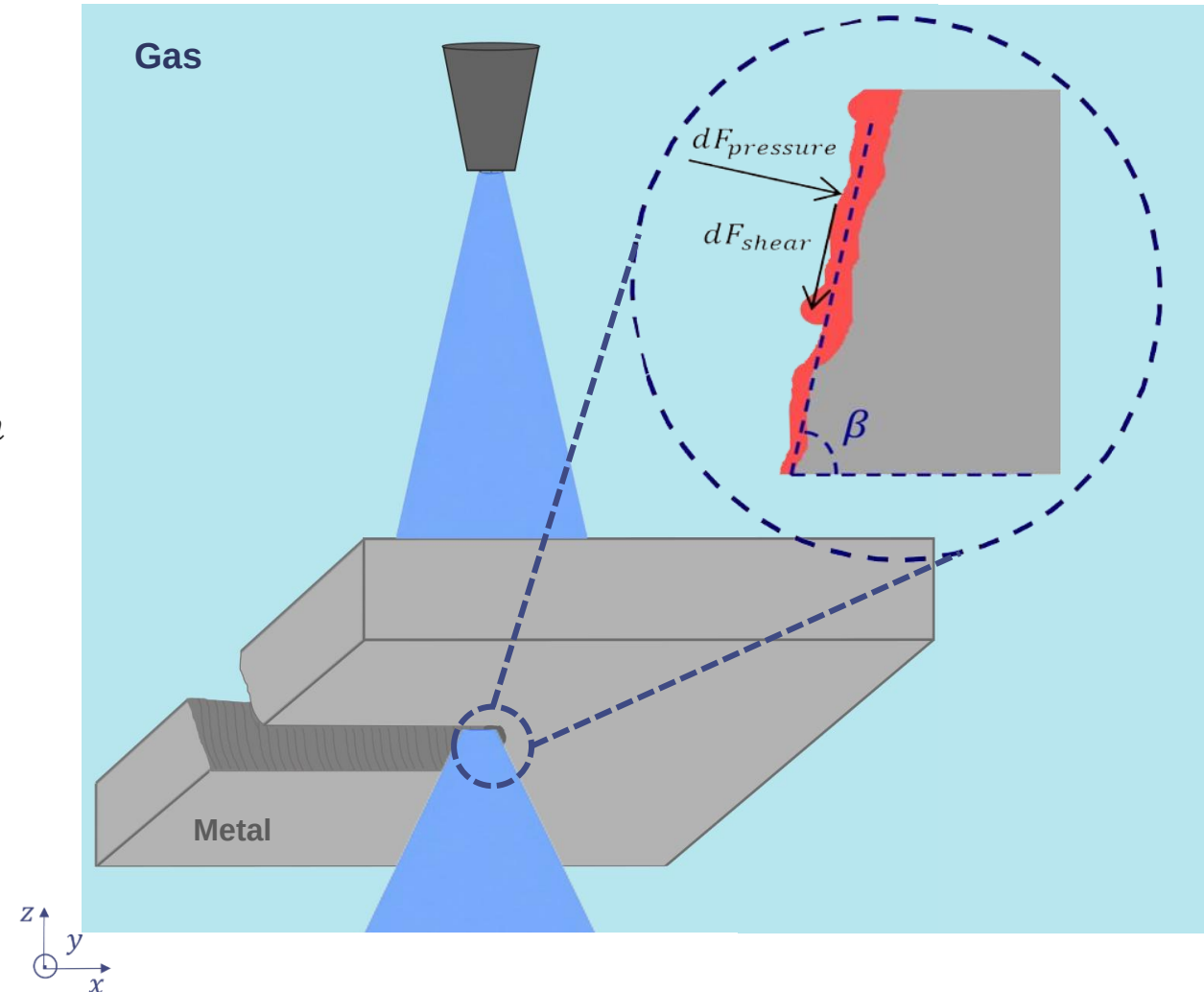
Dynamic pressure: $\overrightarrow{f_{dyn}} = \frac{1}{2} \rho_g |\vec{v}_g|^2 \hat{e}_z$

Friction (shear) force: $\vec{\tau}_{fric} = 2 \sqrt{\frac{\rho_g \mu_g}{d}} |\vec{v}_g|^{3/2} \hat{t}$

- Flow is **turbulent** and **supersonic** for $q_v = 100 - 800 \text{ L/min}$

Proposal :

- Develop a **standalone model** gas domain model
- Extract **stress tensor** at metal – gas **interface**
- Apply** stress tensor in **thermohydrodynamic model**



[6] M. Vicanek et al., *Journal of Physics D: Applied Physics*, 20, pp. 140–145, 1987.

ASSIST GAS EFFECTS

3D Model :

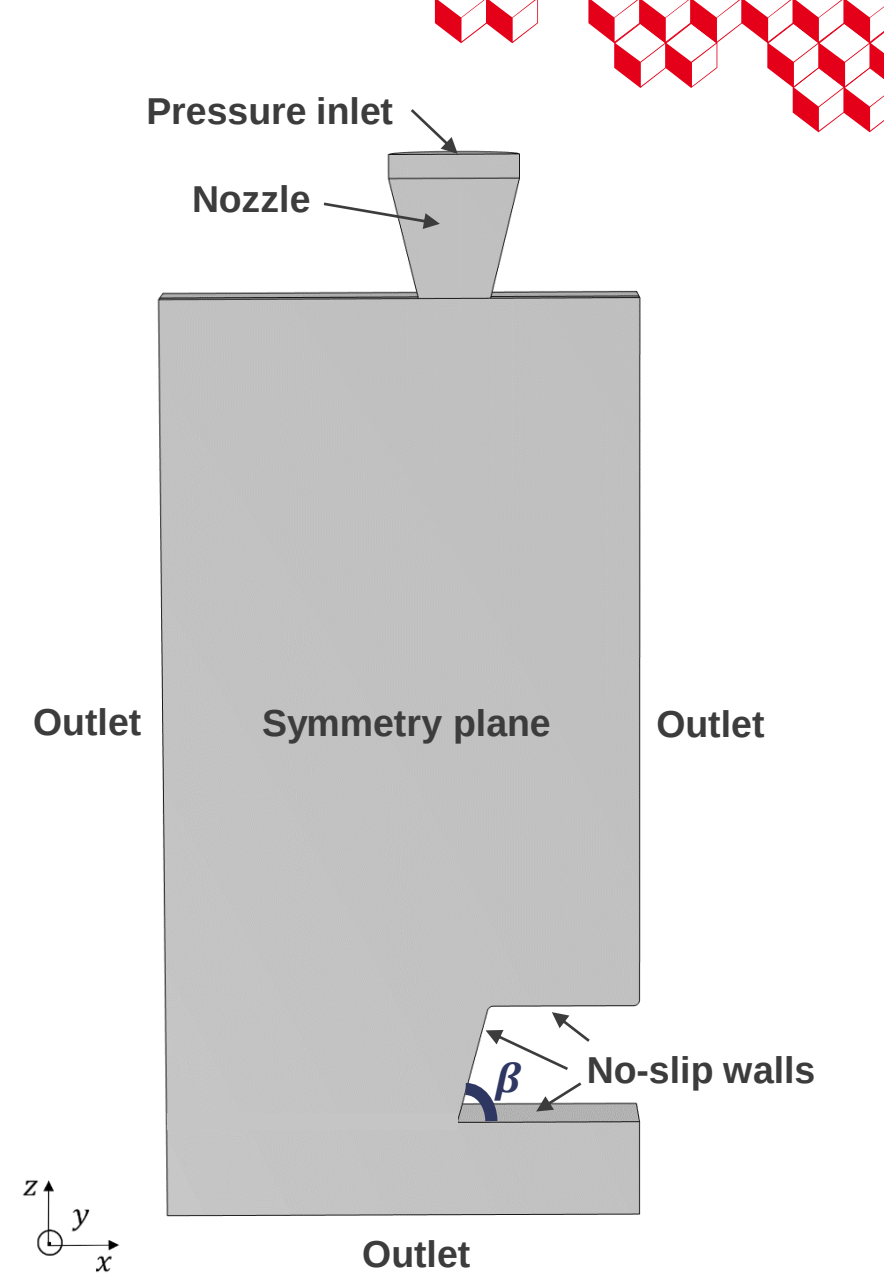
Interface: High-Mach Number Flow

Turbulence model: SST (Shear Stress Transport)

Study: Time-dependent

Material: Air

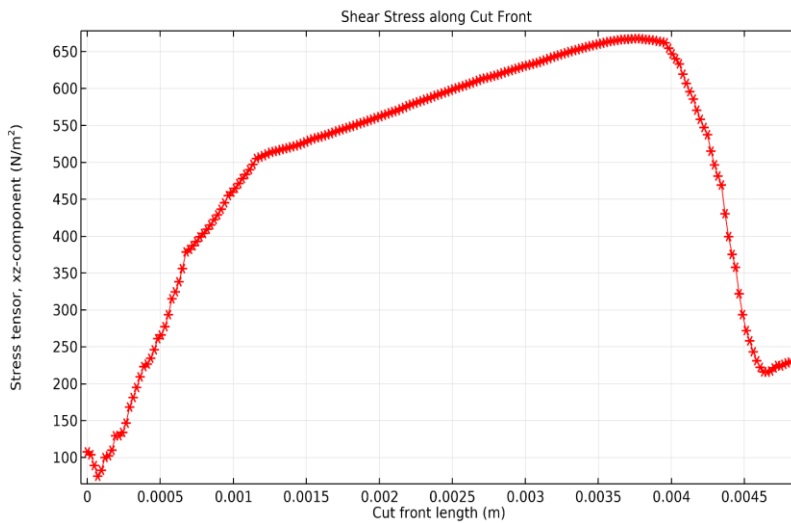
Mesh: Tetrahedral mesh with refinement near walls



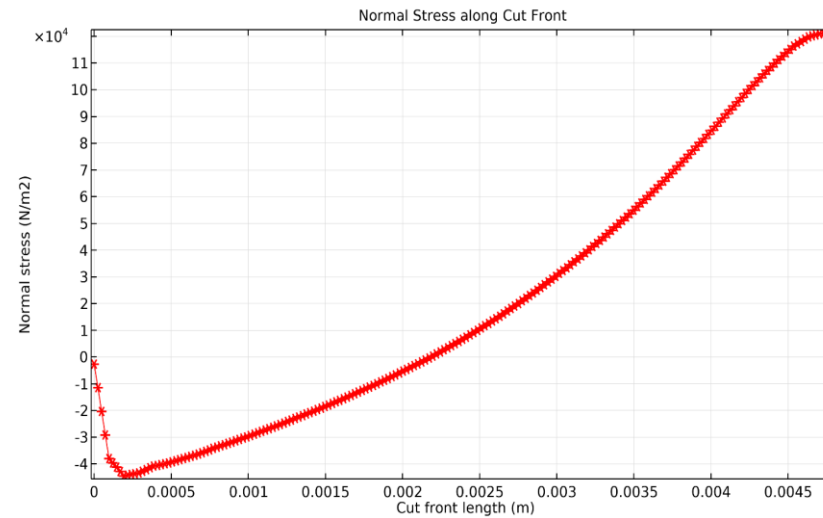
ASSIST GAS EFFECTS

Preliminary results:

Shear stress:



Normal stress:



CONCLUSION

- Extension of a **thermohydrodynamic laser cutting** model to include **oxidation effects**
- Development of a **compressible RANS model** to estimate forces exerted by the **assist gas**

PERSPECTIVES

Thermohydrodynamic model:

- Conduct **experimental campaigns** to calibrate the **oxide fraction**

Assist gas model:

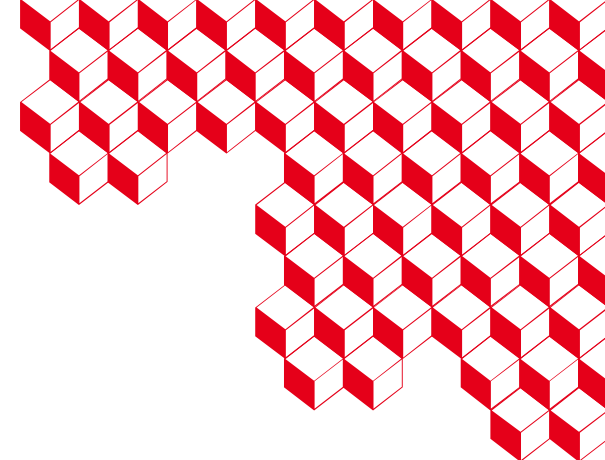
- Coupling of **force distributions** with the **thermohydrodynamic model**



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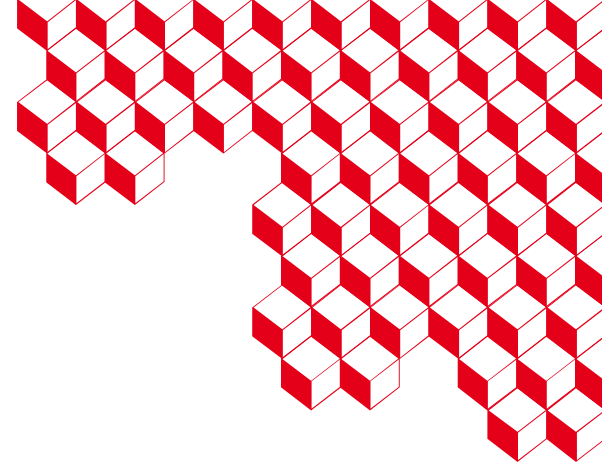
Thank you for your attention

Contact:

carl.tamerian@cea.fr



ANNEX



ASSIST GAS EFFECTS

SST Model

- Combination of $k - \omega$ near the walls and $k - \epsilon$ in the outer flow
- **Accurate** prediction of stress tensor near wall

