Numerical Investigation of Oxidation and Assist Gas Flow in Laser Cutting

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[3] Université Paris-Saclay, CEA, Service d'Études Mécaniques et Thermiques, 91191, Gif-sur-Yvette, France

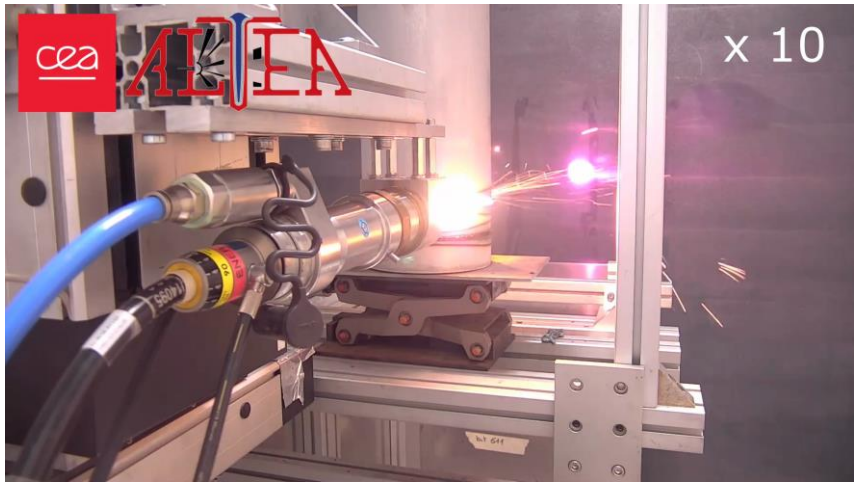
CONTEXT

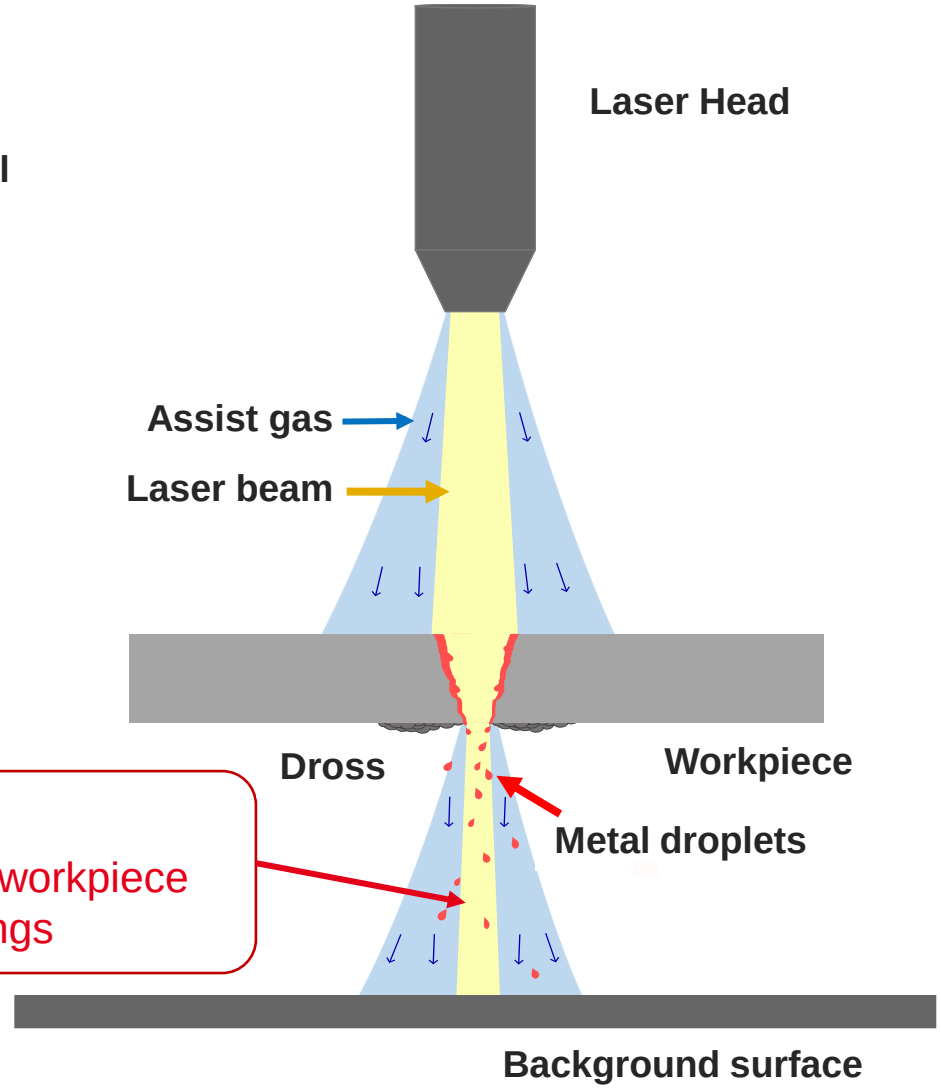
Laser Cutting :

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

Application to Nuclear Decomissioning :

- 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 surroundings

CONTEXT

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

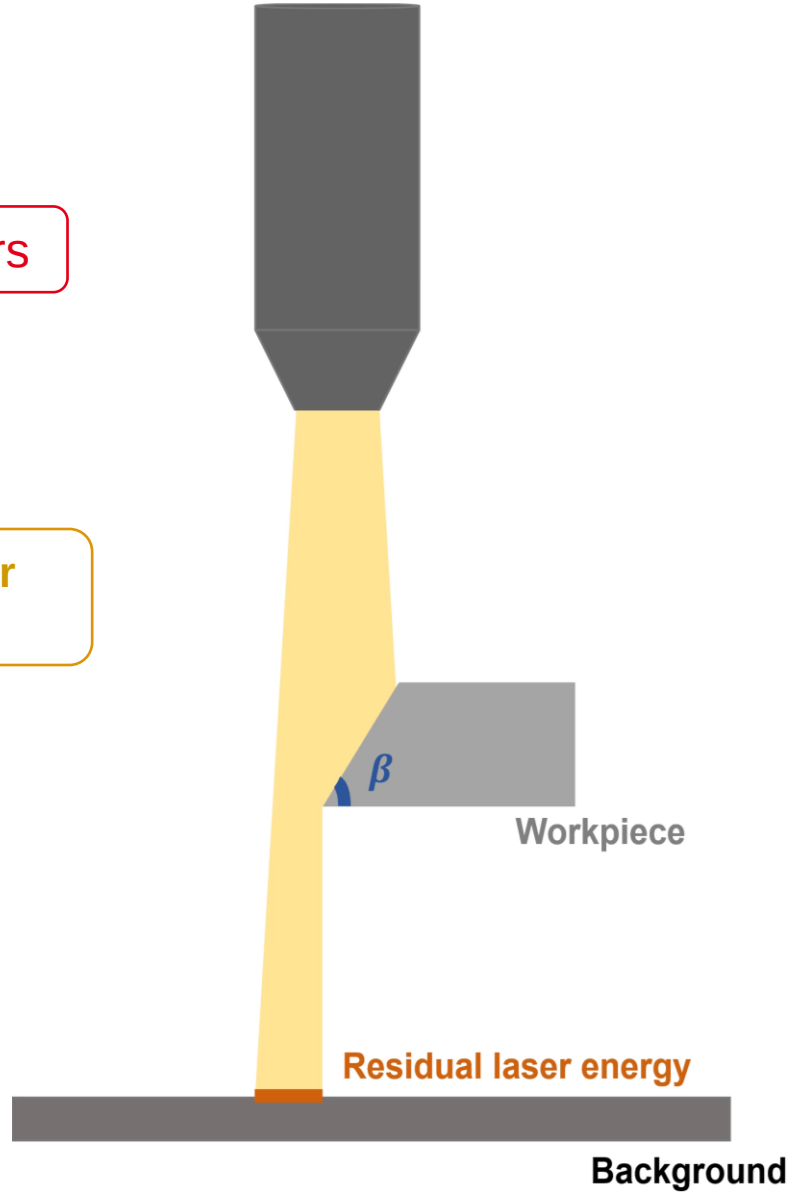
Objective: Estimation of residual laser energy based on operating parameters

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

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

T u ϕ

Fluid flow

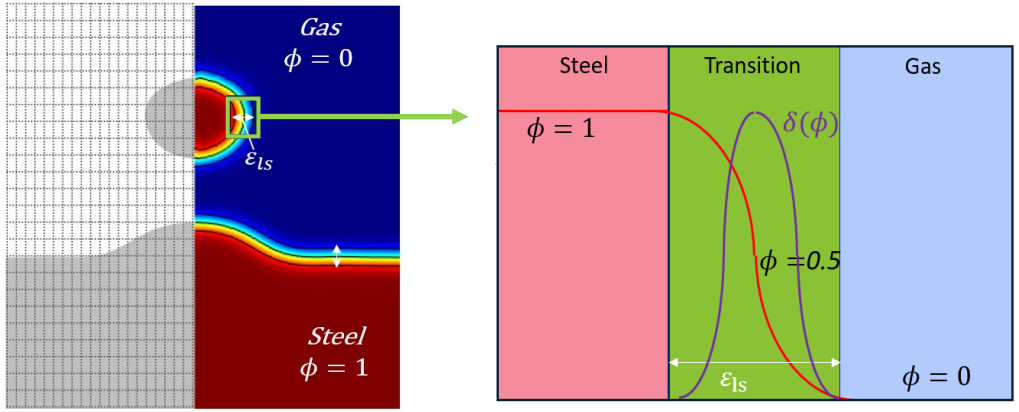
$$\nabla\cdot u=0$$

$$\rho\left(\frac{\partial u}{\partial t}+(u\cdot\nabla)\mathrm{u}\right)=\nabla\cdot\left[-pI+\mu\left(\nabla u+(\nabla u)^T\right)\right]+\left[S_{ST}+S_{Assist}+S_{Darcy}\right]\delta(\phi)$$

u ϕ

Level Set : Interface tracking

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



Level set visualization [3]

[1] R. Meillour, Ph.D. dissertation, Université de Bretagne Sud, 2025.
[3] S. Cadiou, Ph.D. dissertation, Université de Bretagne Sud, 2019.

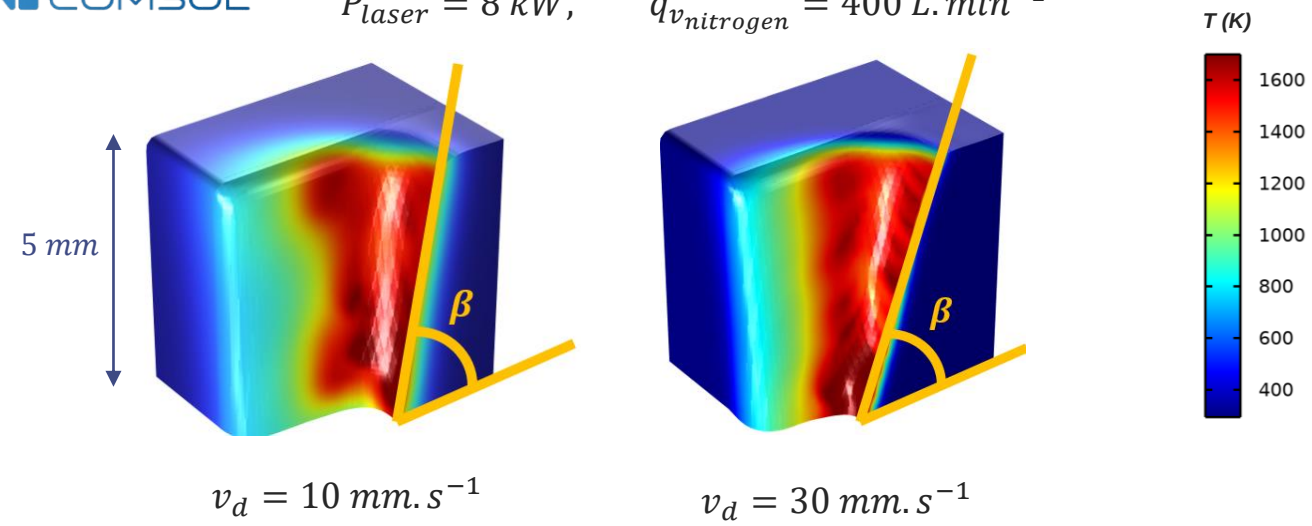
LASER CUTTING MODEL

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

Numerical results:

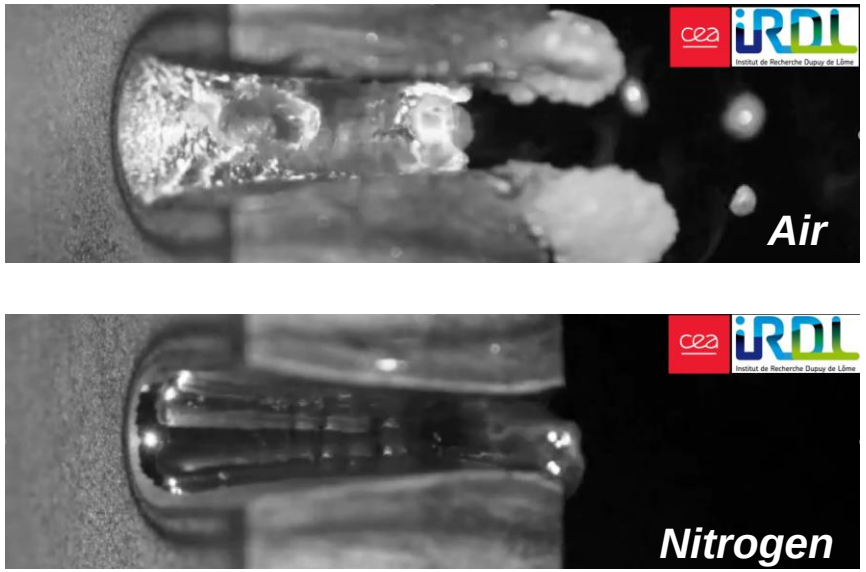
COMSOL

$P_{laser} = 8\ kW,$ $q_{v_{nitrogen}} = 400\ L.min^{-1}$



$v_d = 10\ mm.s^{-1}$ $v_d = 30\ mm.s^{-1}$

Experimental results:



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

Main findings:

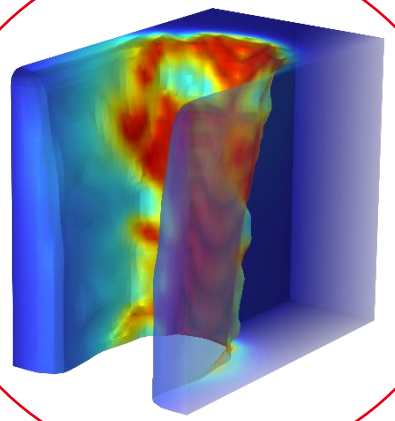
- Dependence of **cut front angle** on **operating parameters**
- Cutting in **air** leads to **larger cut front angles** due to **oxidation** $(\beta_{air} > \beta_{N_2})$

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.

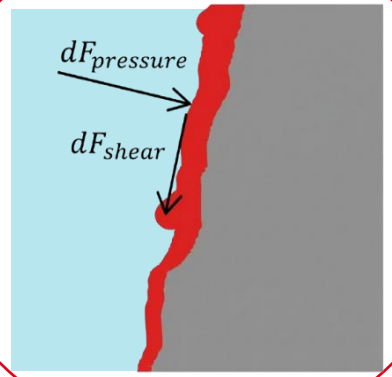
RESEARCH AIMS



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

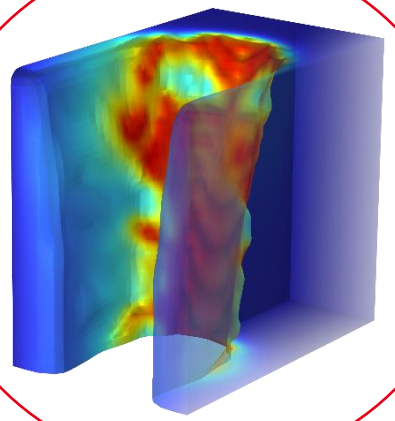


Assist Gas Effects

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

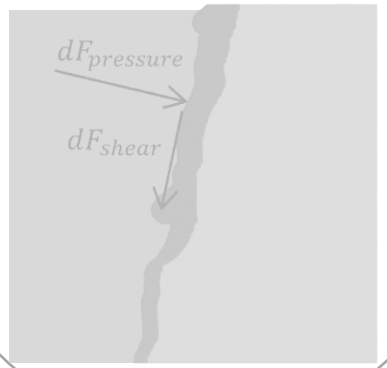
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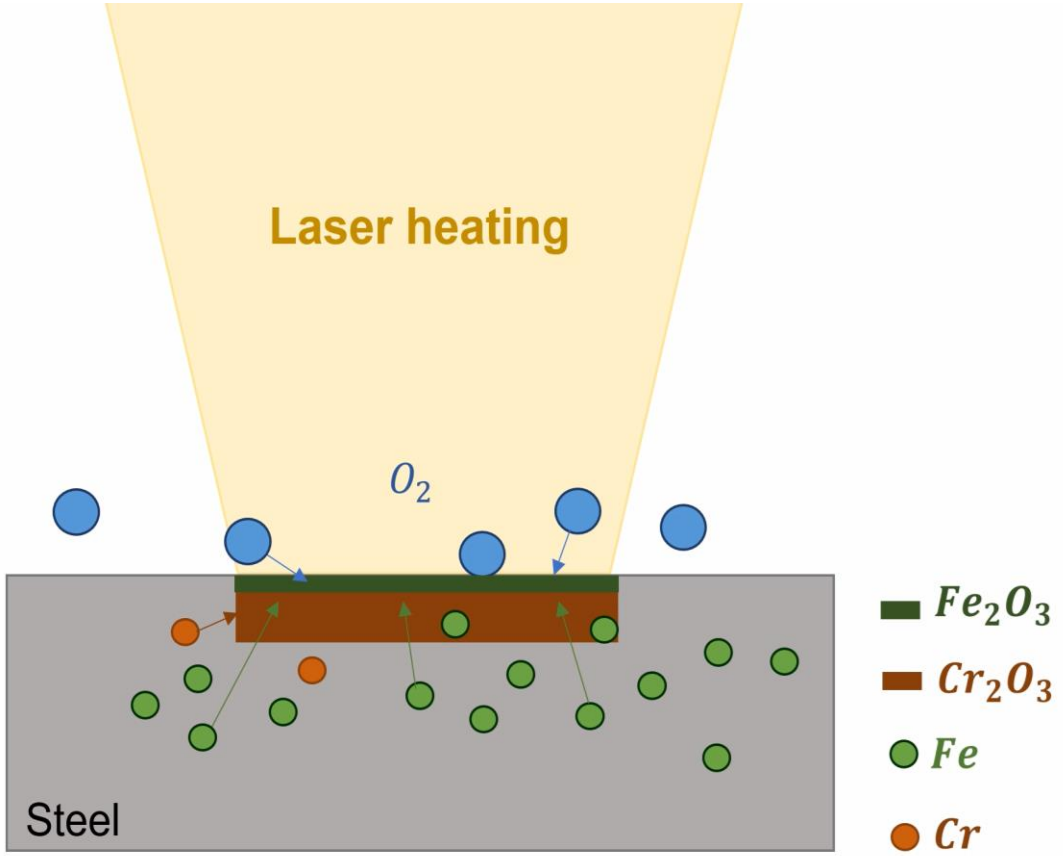
OXIDATION OF 304L STAINLESS STEEL

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

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

In laser cutting:

- Oxidation **can contribute up to 60% of total heat input *** [5]



** Reported for pure O_2 cutting at 900W*

[5] 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 [6]

Proposed oxidation heat source:

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

Added in:

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

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

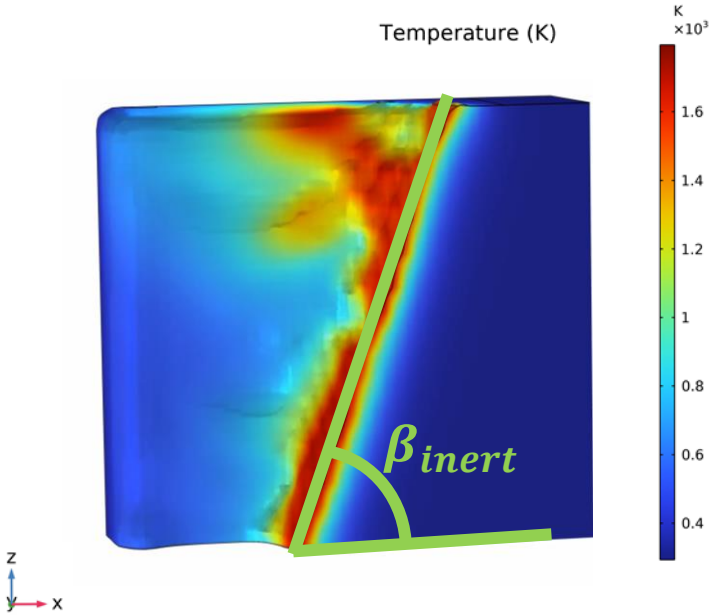
OXIDATION OF 304L STAINLESS STEEL

Preliminary results:

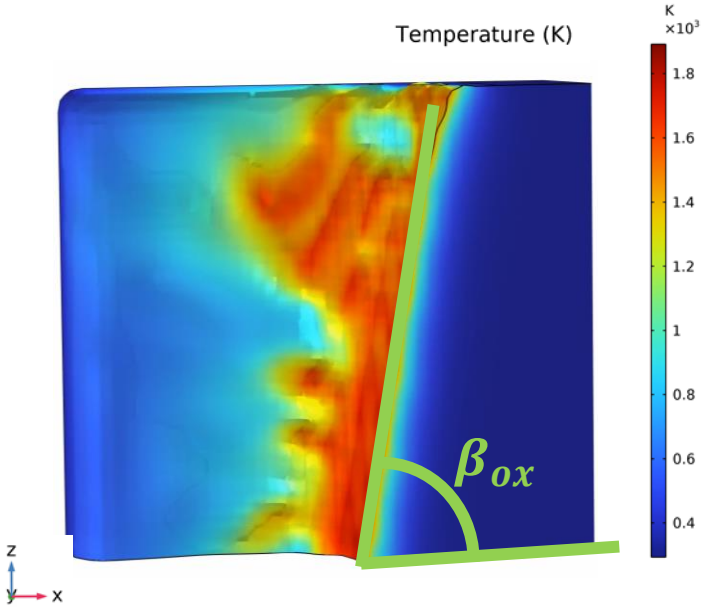
$P_{laser} = 8kW, \quad th = 5mm, \quad v_d = 30mm.s^{-1}, \quad q_v = 100L.min^{-1}$

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

COMSOL



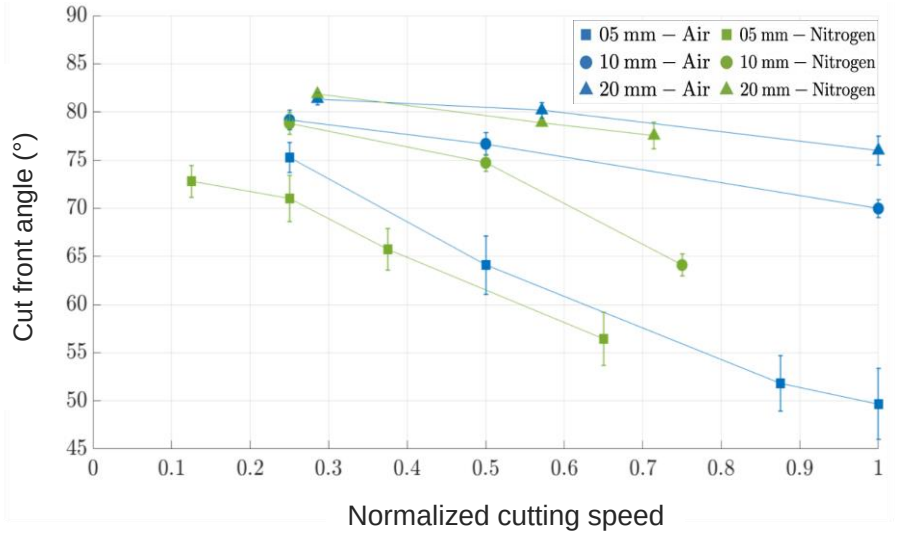
Without Oxidation



With oxidation

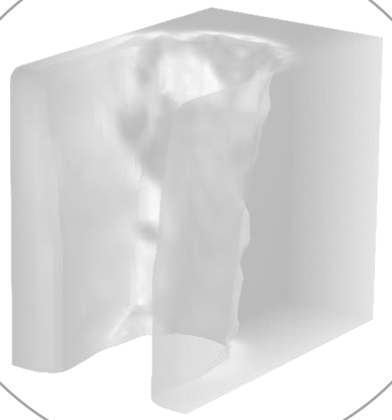
$\beta_{ox} > \beta_{inert}$

Consistent with experiments in [1]



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

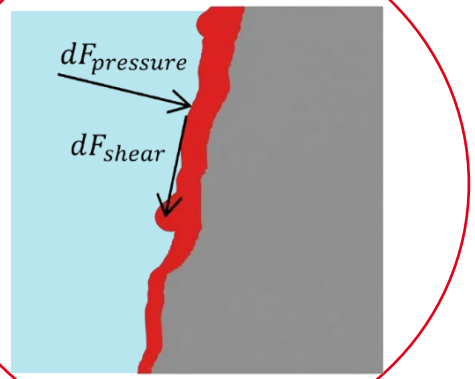
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Physics interface: High-Mach Number Flow

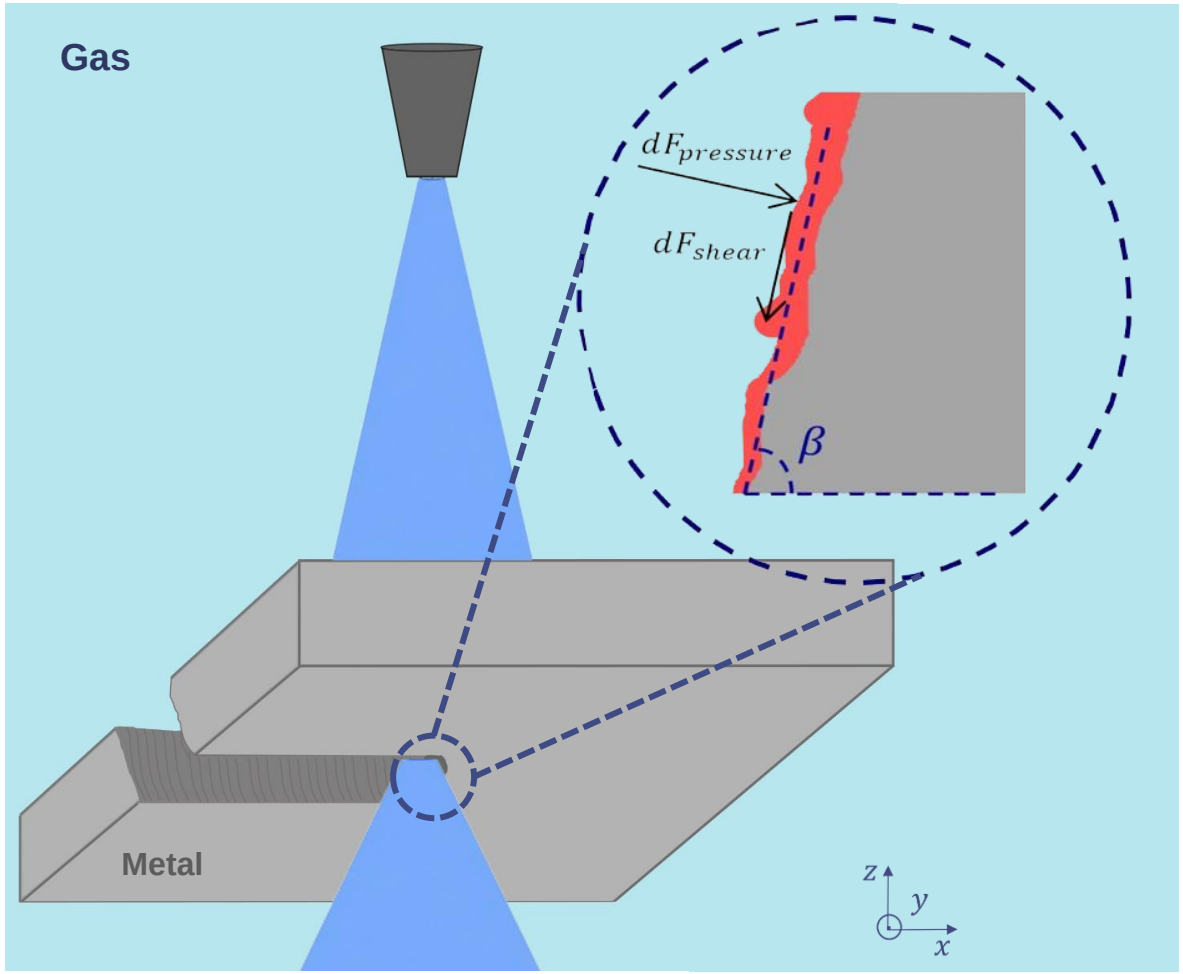
ASSIST GAS EFFECTS

Assist gas effects previously represented via [7]:

Dynamic pressure: $\overrightarrow{f_{dyn}} = \frac{1}{2}\rho_g |\overrightarrow{v_g}|^2 \widehat{e_z}$

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

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



Proposal :

- Develop a **standalone model** gas domain model
- Extract **stress tensor** at metal – gas interface
- **Thermohydrodynamic model**: apply stress tensor distribution as a volumetric force at the interface

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

ASSIST GAS EFFECTS

3D Model :

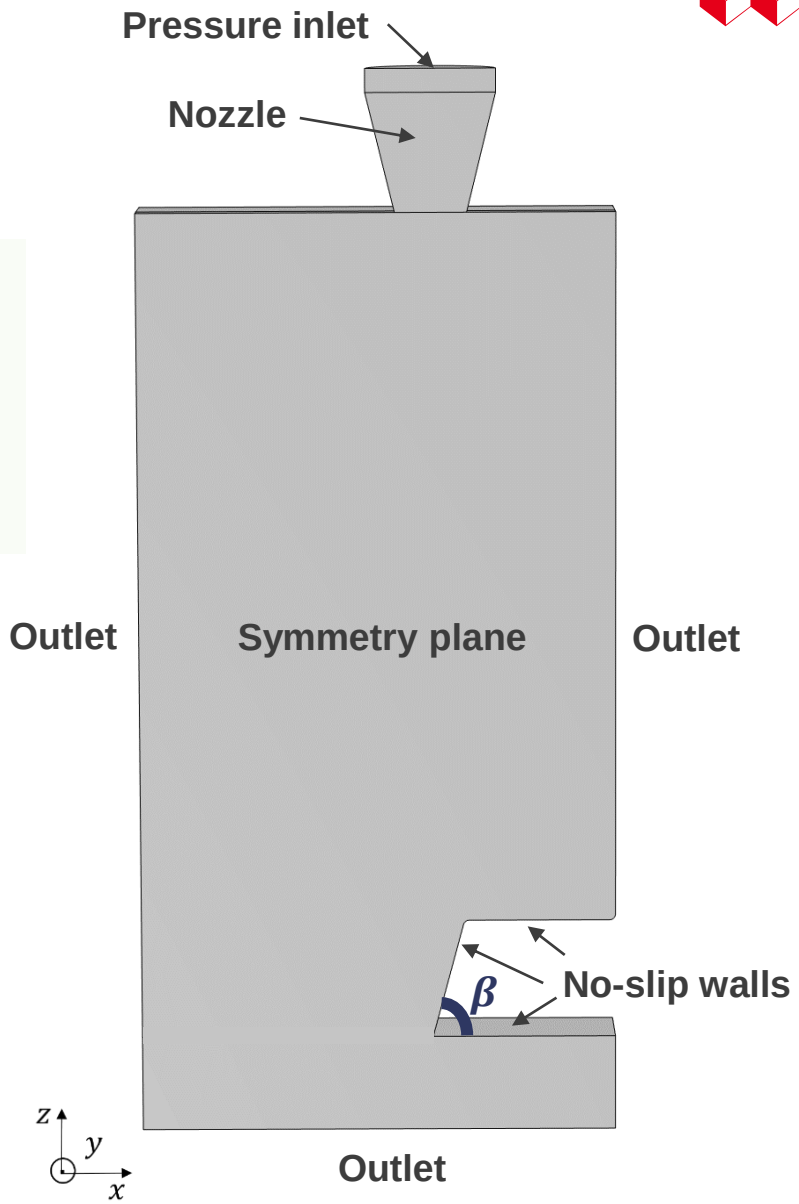
Interface: High-Mach Number Flow

Turbulence model: SST (Shear Stress Transport)

Study: Time-dependent

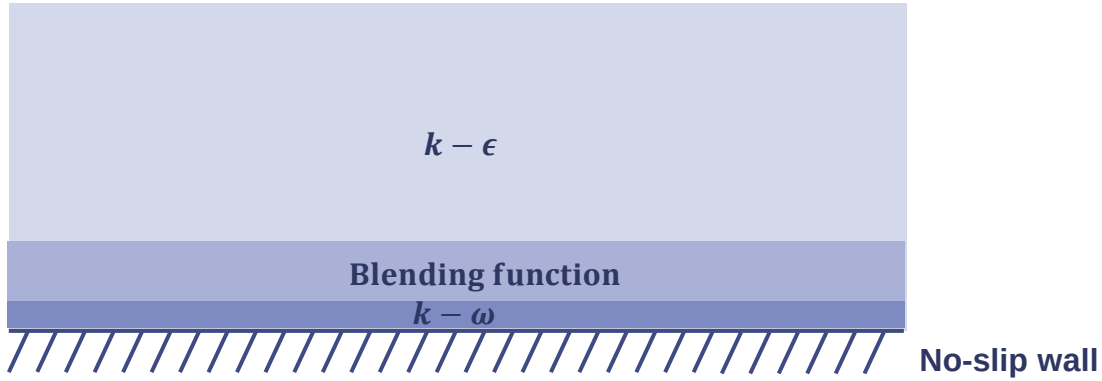
Material: Air

Mesh: Tetrahedral mesh with refinement near walls



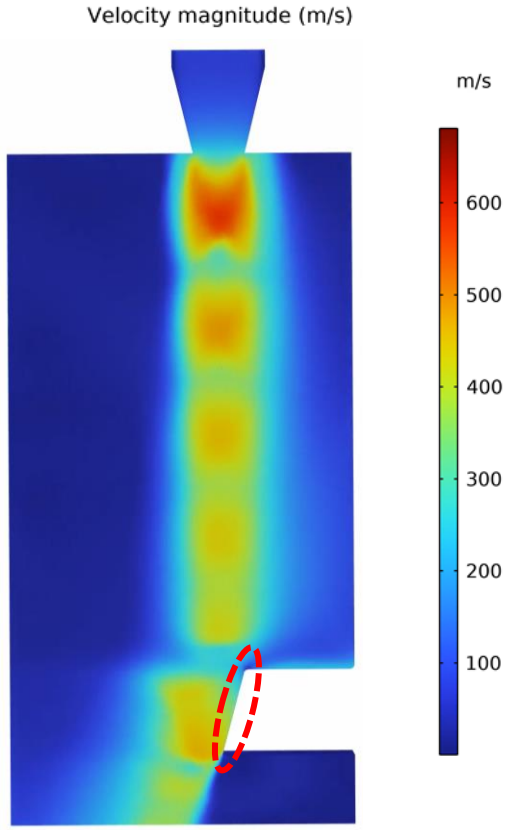
SST Model

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



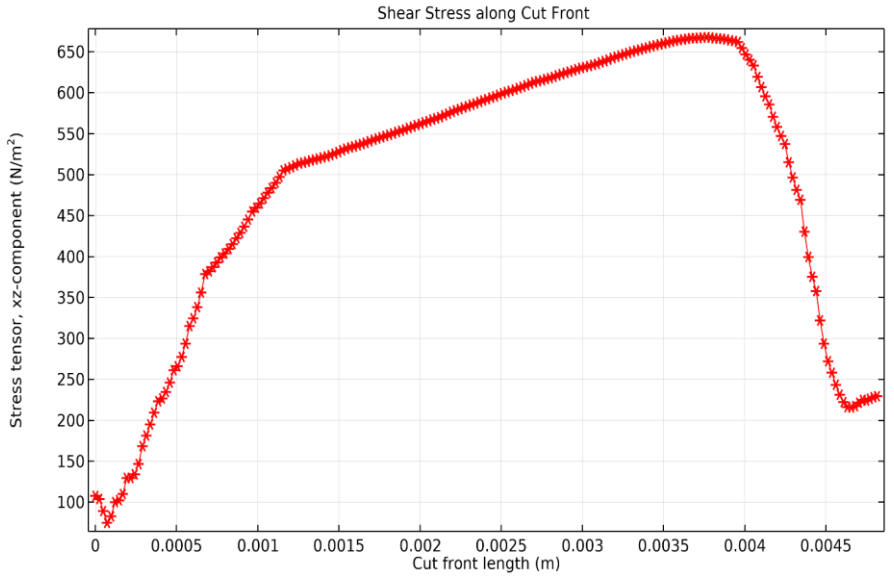
ASSIST GAS EFFECTS

Preliminary results:

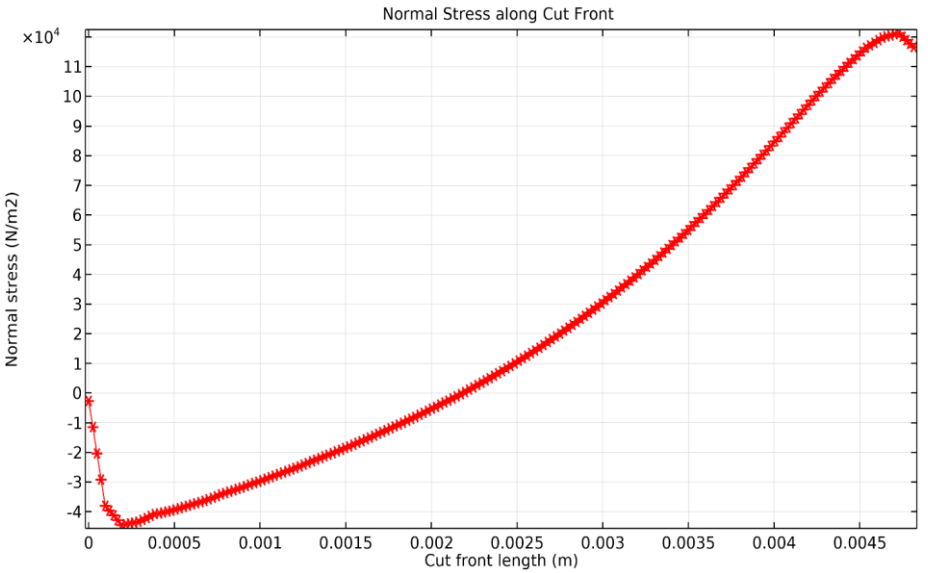


Velocity plot with $P_{inlet} = 5.6$ bar

Shear stress:



Normal stress:



Non-uniform force distribution along the cut front

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**

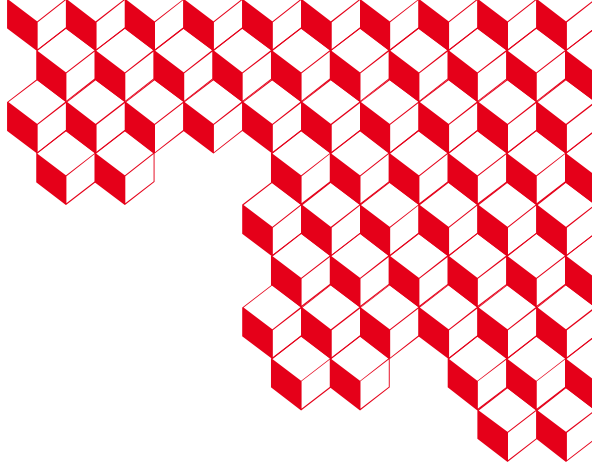
Assist gas model:

- Perform a **parametric study** of different **cut-front angles**
- Coupling of **force distributions** with the **thermohydrodynamic model**



isas





Thank you for your attention

Contact:

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