ArcelorMittal

In collaboration with:

Université de Bretagne-Sud

LIMATB Laboratoire d'Ingénierie des MATériaux de Bretagne

Optimization of welding parameters using 3D Heat and fluid flow modeling of keyhole laser welding

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COMSOL CONFERENCE 2015 GRENOBLE

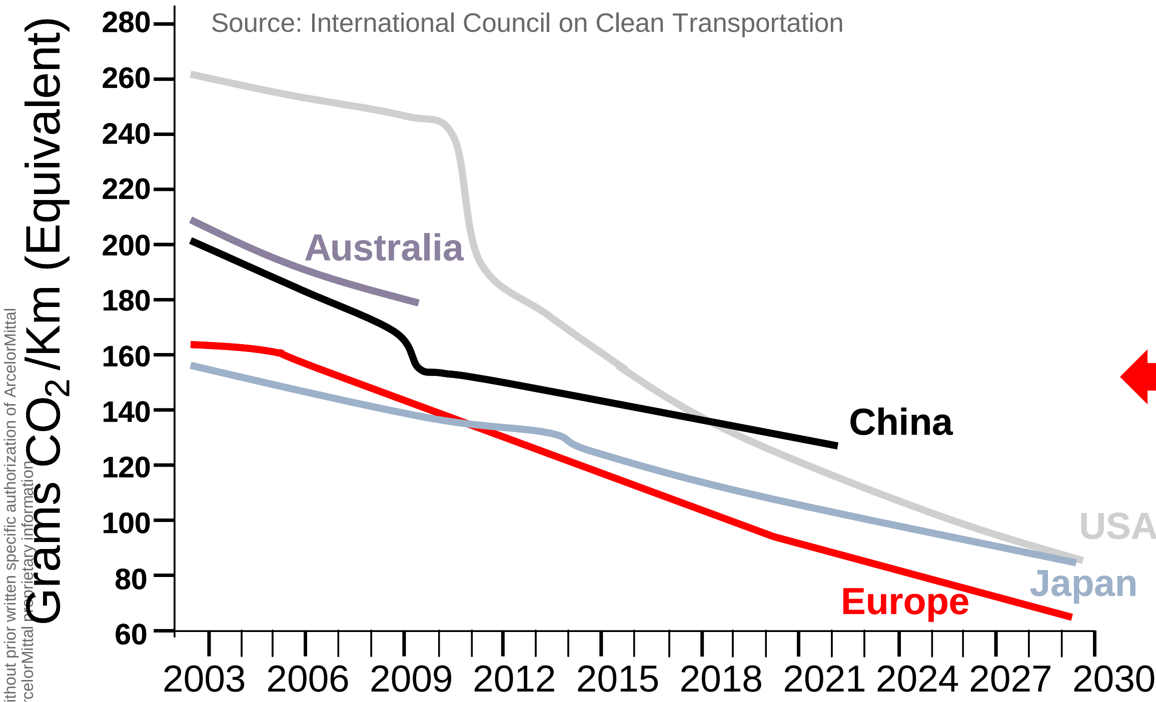
Agenda

- **I – Introduction**
  - Laser Welded Blanks Solution
  - Need of numerical model to estimate weld geometry and its defects

- **II – Numerical model presentation**
  - **Physics of laser welding**
  - **Numerical model**
    - Heat and fluid flow
    - Laser – electromagnetism
  - **Results and discussion**

- **III - Conclusions**

Weight Reduction: a Worldwide Challenge Driven by Emission Reduction



Main challenges faced by the automotive industry:

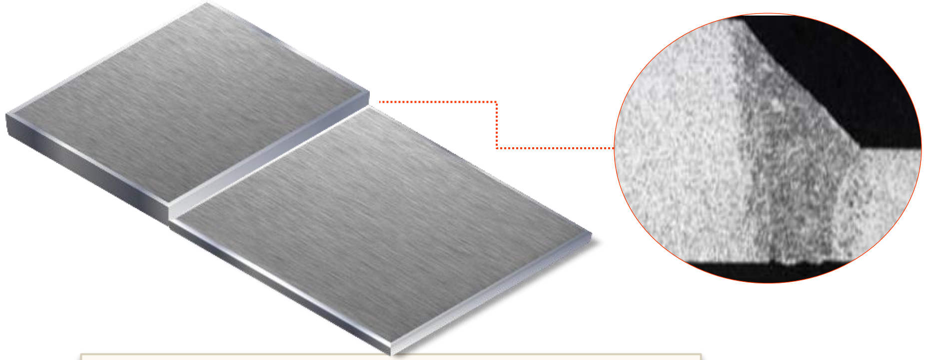
– Enhanced safety performances
– Sustainability, affordability
– Geographical car production shifts
– Reduced emissions requirements

ArcelorMittal Steel Products
Range of new products (Usibor® 2000, Ductibor® 1000, Fortiform®…)

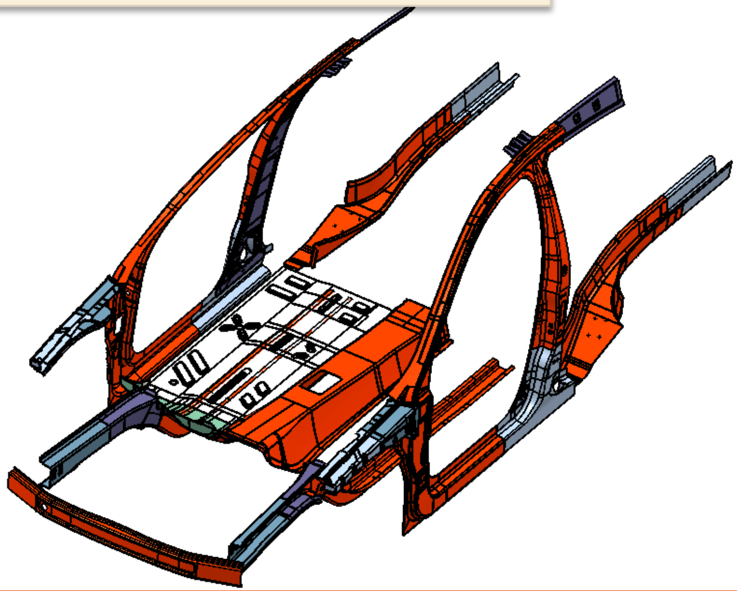
Customer Engineering Capabilities
BiW is a large contributor to weight reduction, Powertrain also important

ArcelorMittal Engineering Support
Partnerships with OEM to identify best solutions in weight and cost (LWB…)

Laser Welded Blanks
An efficient tool for mass reduction



Laser Welded Blanks: Butt weld



very high mass savings (often more than 20%) were achieved thanks to the use of Laser Welded Blank hot-stamped solutions (16) on key structural parts
(S-In-Motion project)

- Potential applications
  - B-pillar
  - Front side member
  - Rear side member
  - Tunnel
  - Door-Ring

Laser welded blanks offer an effective way to reduce weight while maintaining performances

Loading of the Parts during Crash

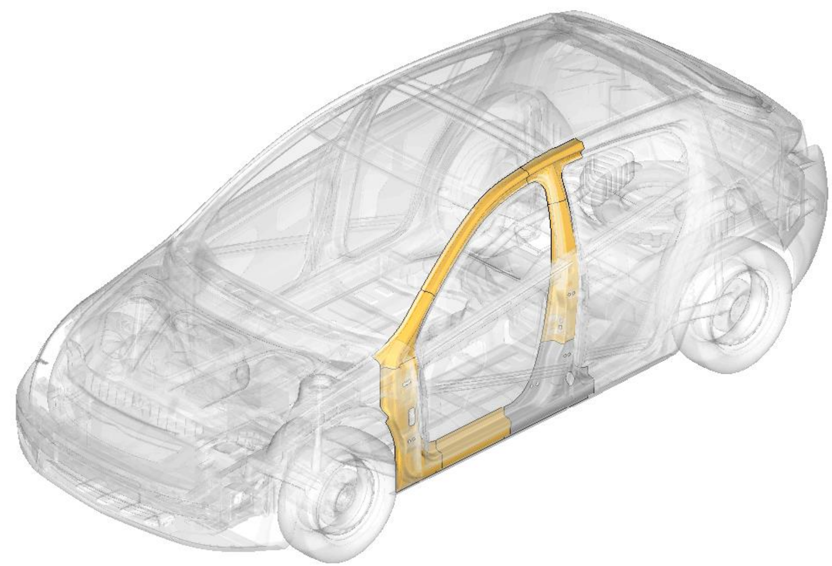
Weld loaded in severe conditions

- During crash test, the parts and the welds can be loaded in severe conditions.

Example of small overlap crash behavior – Acura MDX

Source: Honda

Example of crash behavior of lateral structure in Euro NCAP AE-MDB side impact

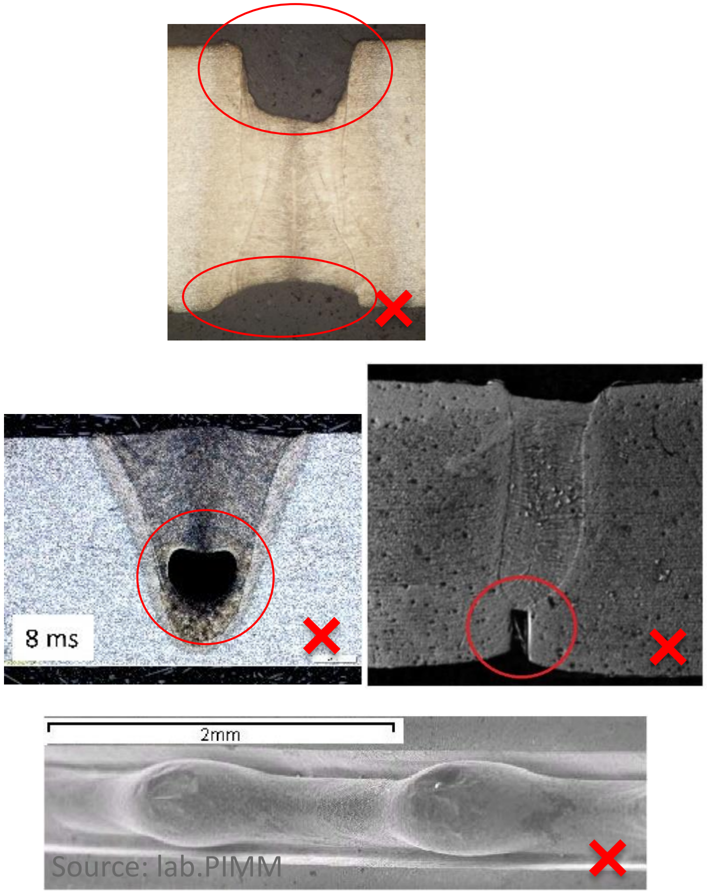


Weld defect

Main parameter influencing the mechanical performances

- Weld defects such as undercut, underfill, partial penetration, drop through are function of the welding conditions
  - Most weld failures (under static or dynamic solicitations) originate from weld joint defects because it is the source of stress concentration

➢ In order to avoid weld geometry defect, a numerical model is needed including the unsteady dynamical behavior of the keyhole and fluid flow in melt pool

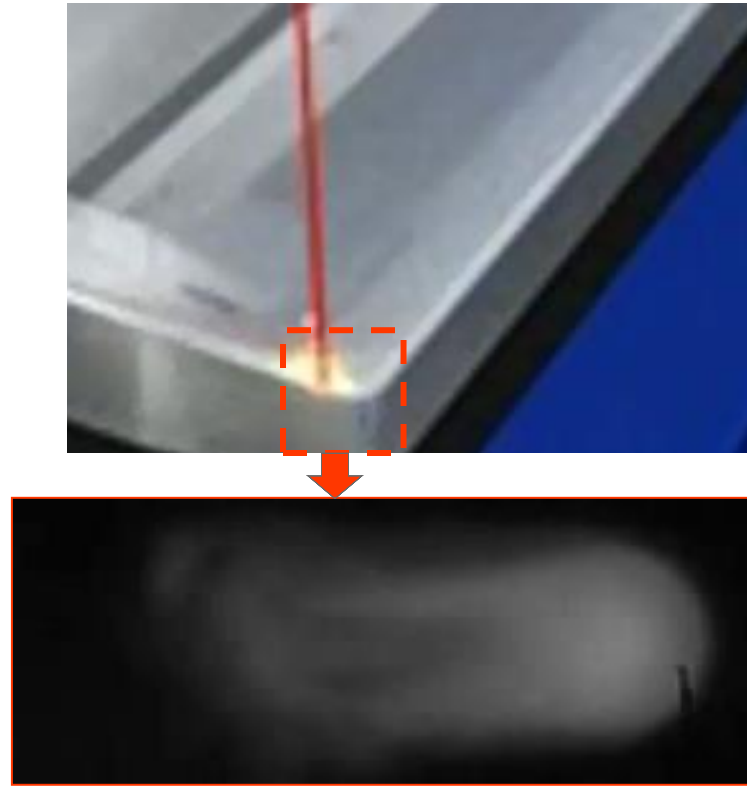


Weld defects to be avoided

Why Comsol multiphysics model ?

- The final goal is to develop a simulation tool that will provide
  1. A fundamental understanding of the physical phenomena that play a role in keyhole laser welding
  2. The fluid flow around the Keyhole and its effect on the weld stability
  3. The accurate weld seam geometry and its defects

- University partnership: University Bretagne Sud: Numerical competencies in multi-physics modeling



Coaxial view of laser welding

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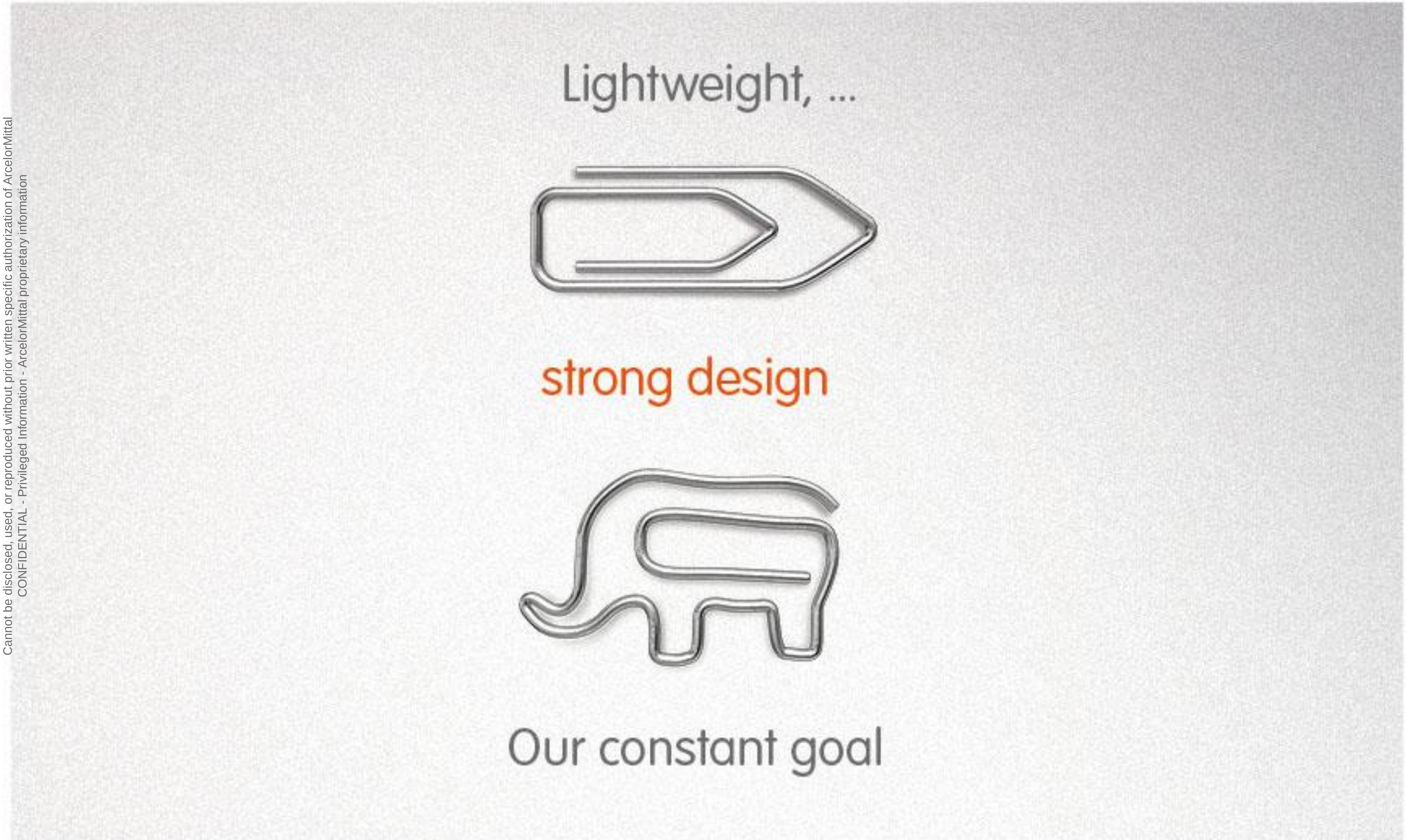
Numerical model presentation



Laser welding in keyhole mode – A multiphysic problem:

Optic / electromagnetism :

- Laser reflections
- Material absorption

Heat transfer :

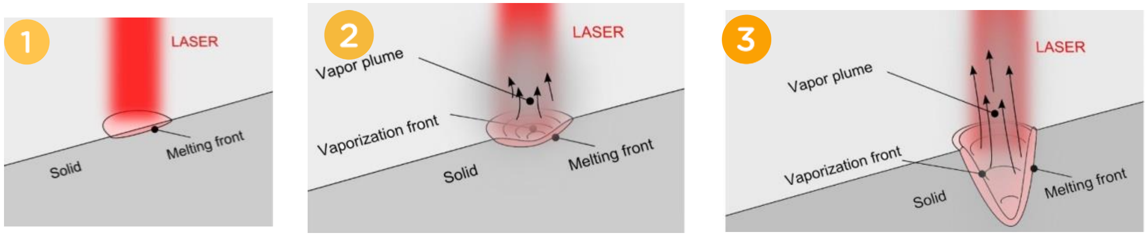
- Conduction, convection
- Radiation
- Latent heats

Fluid mechanics:

- Flows in liquid and gas
- Surface tension, gravity
- Vaporization, recoil pressure
- Vapor plume

Top view of laser welding (PIMM)

Bottom view of laser welding (PIMM)



Multiphysic modeling

Main issues / opportunities:

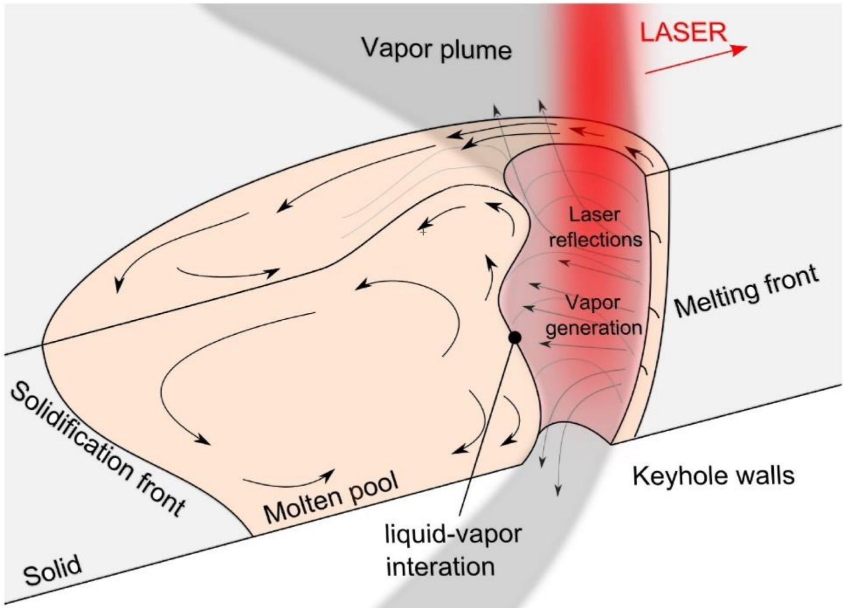
- Vaporization
- Dynamic tracking of liquid/vapor interface
- Multiple reflections of laser

COMSOL

Governing equations :

Heat equation:

$$\rho\, c_p^{\ *} \left[\frac{\partial T}{\partial t} + \vec{u}.\nabla T \right] = \nabla.\left(\lambda \nabla T\right) + I_{laser} + Q_{vap}$$



Navier-Stokes equations

$$\rho\left(\frac{\partial \vec{u}}{\partial t} + \left(\vec{u}.\nabla\right)\vec{u}\right) = \nabla.\left[-PI + \mu\left(\nabla\vec{u} + \left(\nabla\vec{u}\right)^T\right)\right] + \rho\,\vec{g} - \rho\beta_l\left(T - T_{fusion}\right)\phi\,\vec{g} + K\left(T\right)\vec{u} + \left(\gamma.\vec{n}\kappa\right)\delta\left(\phi\right)$$

floatability — Darcy condition — Surface tension

Assumptions: - Newtonian fluids
- Incompressible
- Laminar flows

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Vaporization problem:

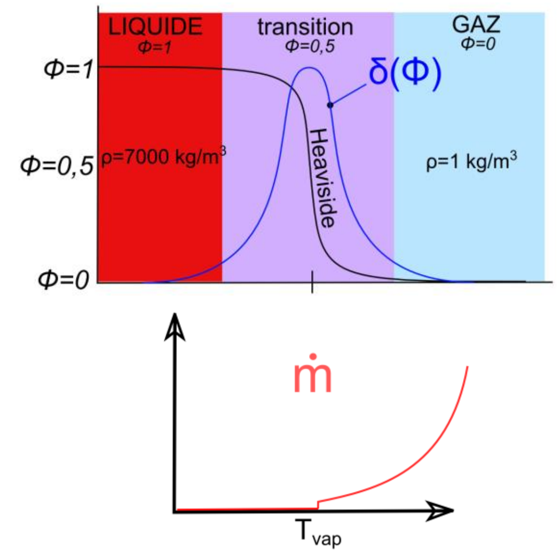
Mass conservation :

Away from interface

$$\nabla.\vec{u} = 0 \quad \rightarrow \quad \nabla.\vec{u} = \dot{m}\,\delta(\phi)\left[\frac{\rho_l - \rho_v}{\rho^2}\right]$$

$$\dot{m} = \sqrt{\frac{m}{2\,\pi\,k_b}}\,\frac{p_{sat}(T)}{\sqrt{T}}\left(1-\beta_r\right)$$

[Hirano-Fabbro 2011]



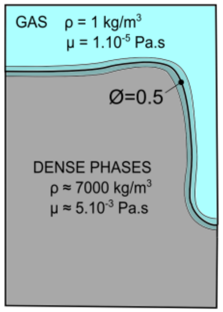
→Recoil pressure; important fluid flow

Dynamic tracking of liquid/vapor interface : Level set method *CFD module Comsol*

Fixed mesh; Definition of a variable φ in all the elements

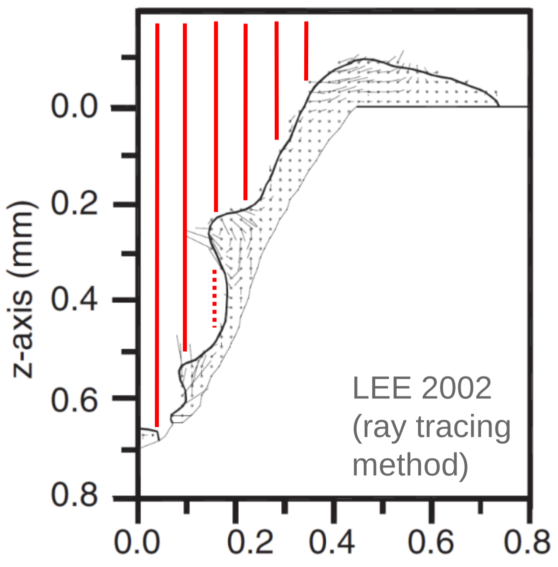
Transport of this variable using the fluid flow calculation:

$$\frac{\partial\phi}{\partial t} + \vec{u}.\vec{\nabla}\phi - \dot{m}\,\delta(\phi)\left(\frac{1}{\rho}\right) = \gamma_{ls}\nabla\cdot\left(\varepsilon_{ls}\nabla\phi - \phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|}\right)$$



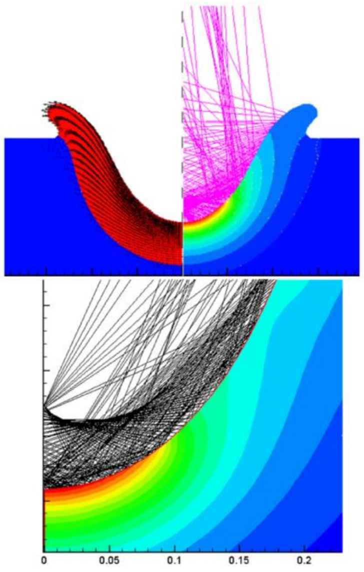
Energy deposition and laser reflections:

Mask effect:



LEE 2002
(ray tracing
method)

Concentration effect :



MEDALE 2007
(ray tracing method)

<u>New approach developed</u> :

Laser described in its wave form (Maxwell's equations) :

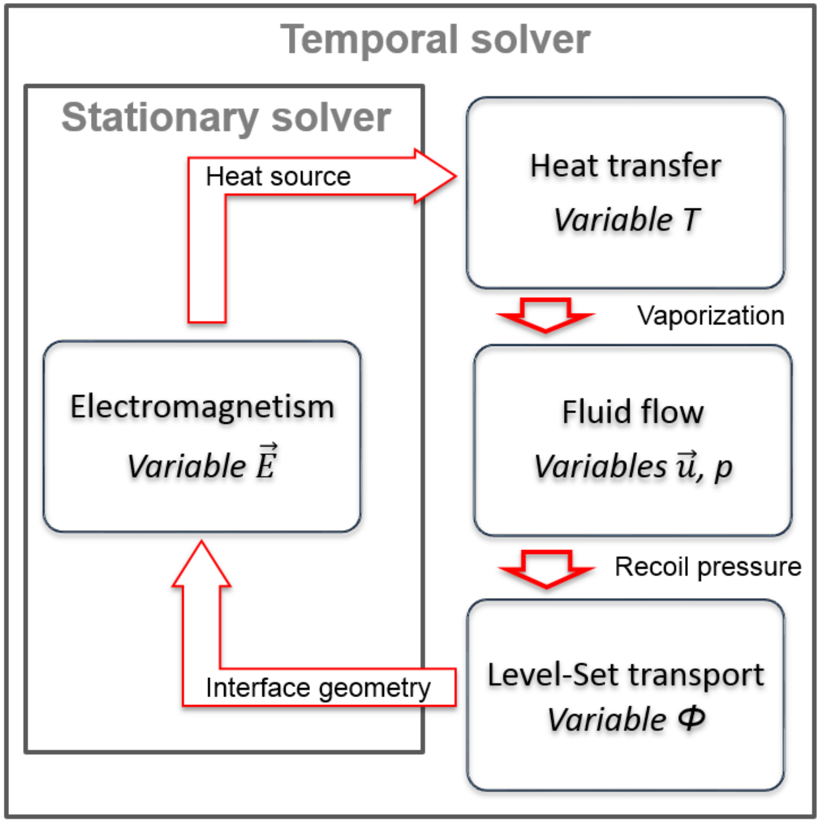
$$\frac{\Delta\vec{E}}{\mu_r} + k_0{}^2\left(\varepsilon_r - \frac{j\,\sigma}{\omega(\lambda)\,\varepsilon_0}\right)\vec{E} = \vec{0}$$

Potential vector formulation

→ *RF module Comsol*

Coupling: heat / fluid flow / level set method / electromagnetism

Characteristic time: ***Wave:*** *3mm at 3.10^{8}m/s < 1ns* ***heat transfer / fluid:*** *> 1 ms*



Method usable in every configuration (2D - 2D axi- 3D)

Numerical trick:

- λ laser x50
(1,06 µm -> 50 µm) for mesh convenience

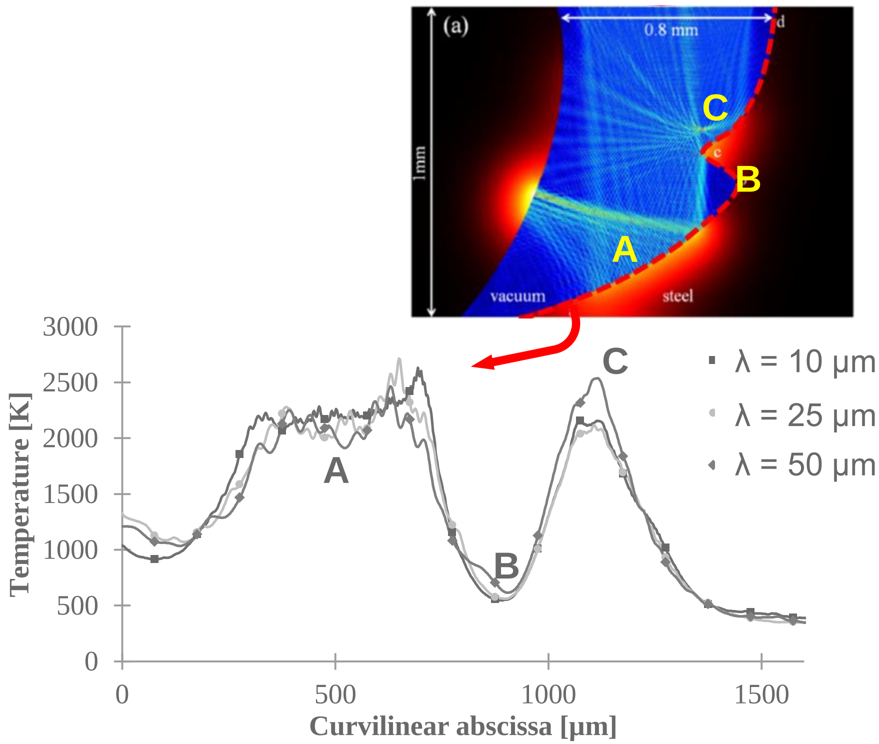
- Snell-Descartes law conserved

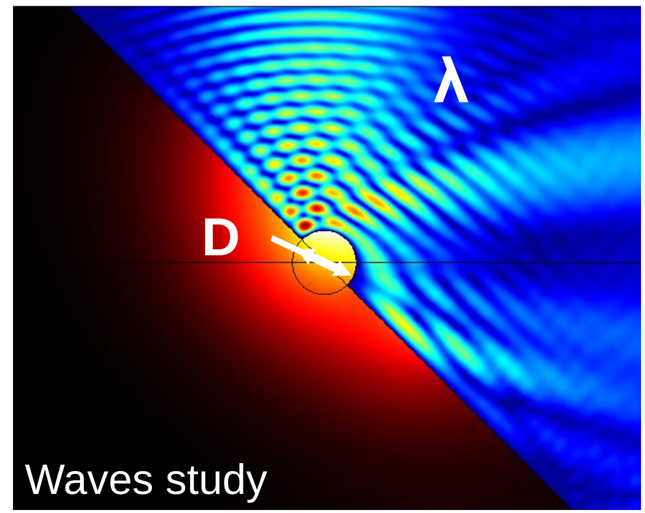
But need to:

1 - validate the wave propagation for different geometries

2 - adapt material properties to keep the real absorption coefficient

1st step : Wave propagation?





1 < D < 200 µm et 10 < λ < 50 µm

- Problem for 200 µm
- Wavelength finally used: λ = 50 µm

- Differences with singularities of dimensions < λ

(here if D < 50 µm)

→ no effect of increasing λ (50 µm) for keyhole geometry with imperfection more than 50 µm

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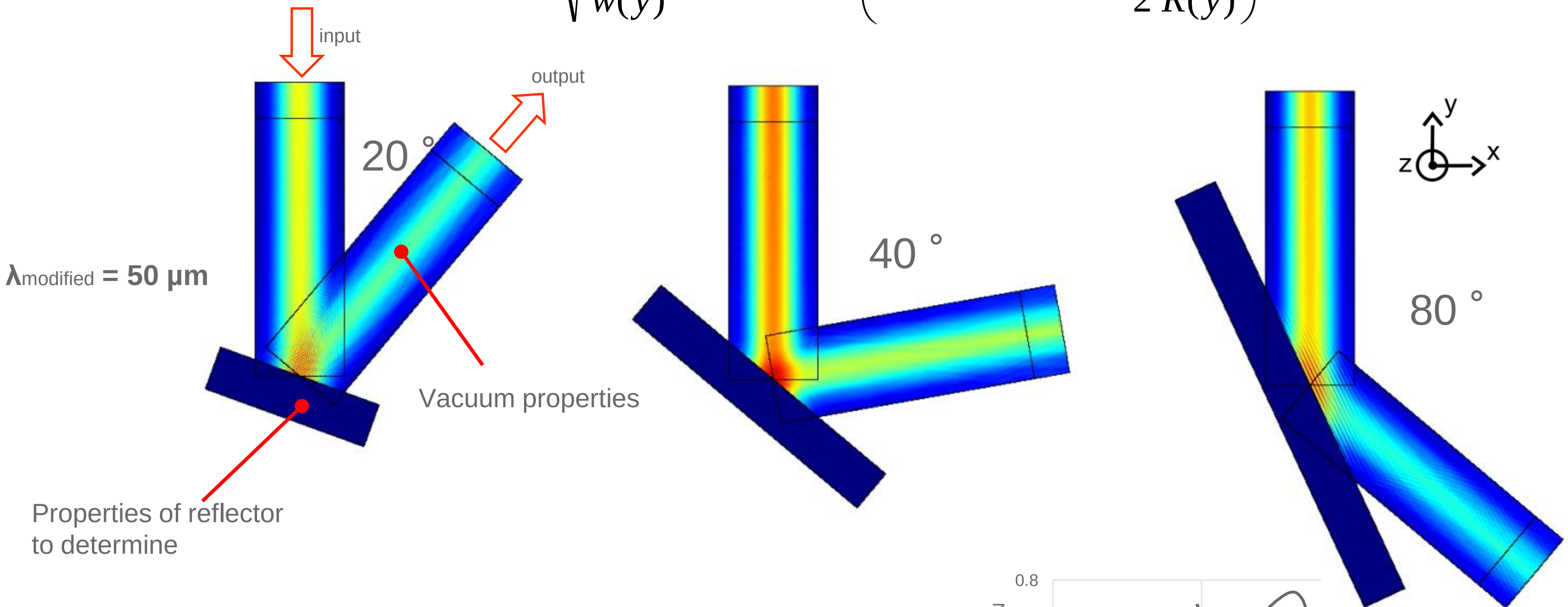
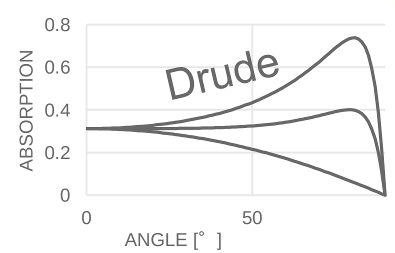
2nd step : Development of a specific model to identify equivalent reflections properties

Laser input: $\vec{E}_{(x,y,z)} = E_0 \sqrt{\frac{w_0}{w(y)}}\, e^{-\left(\frac{x}{w(y)}\right)^2} \cos\left(\omega_0 - ky + \eta(y) - \frac{k\,x^2}{2\,R(y)}\right)\vec{e}_z$

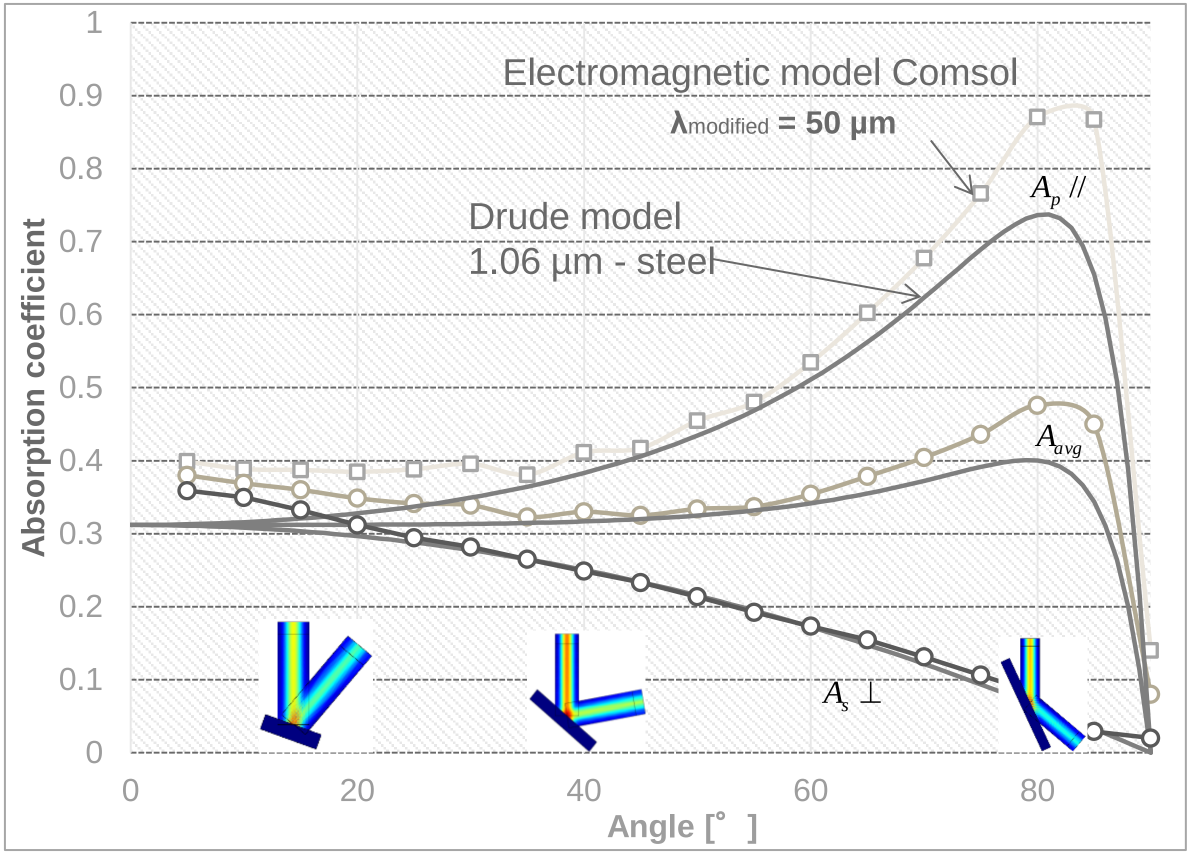


Absorption coefficient $\alpha = 1 - \frac{E_{outlet}}{E_{inlet}}$

Goal:



2^{nd} step: Development of a specific model to identify equivalent reflections properties



Identified properties of equivalent material:

($\lambda_{modified}$ = 50 µm)

- Complex relative permittivity

  $\varepsilon_r = \varepsilon'(1\text{-}j.\tan\delta)$

  ε' = 86, $\tan\delta$ = 0,6

- Electric conductivity :

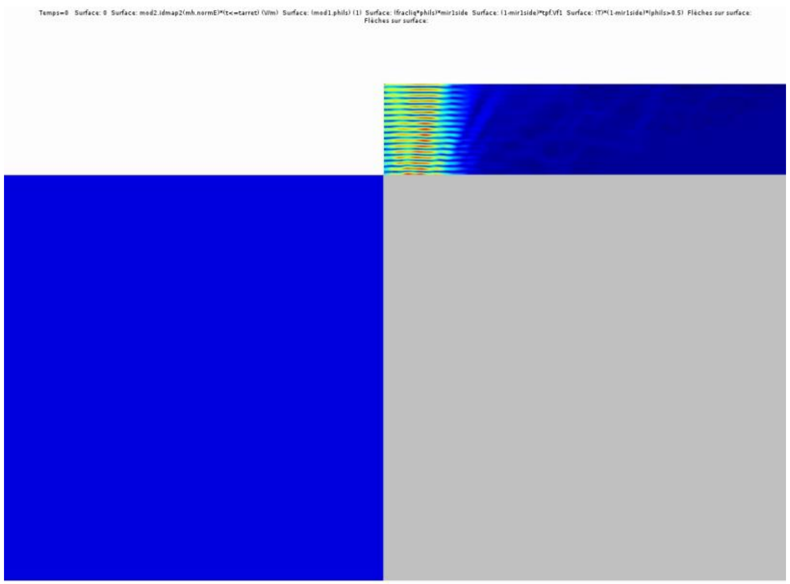
  $\sigma = 0$

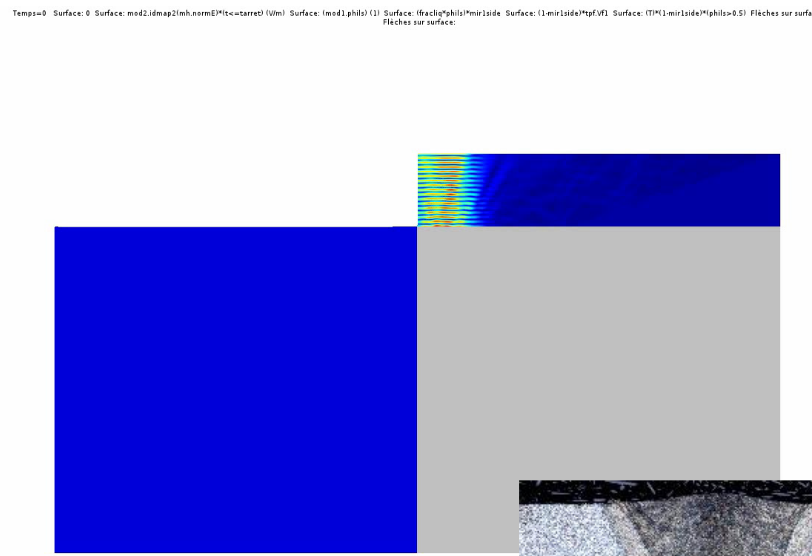
- Relative permeability :

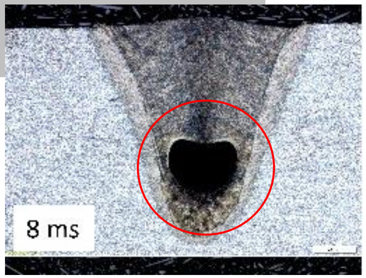
  $\mu_r = 1$

Conclusion : Laser propagation and reflections modeled with $\lambda_{modified}$ = 50 µm **under wave form**

Numerical Results for two laser parameters



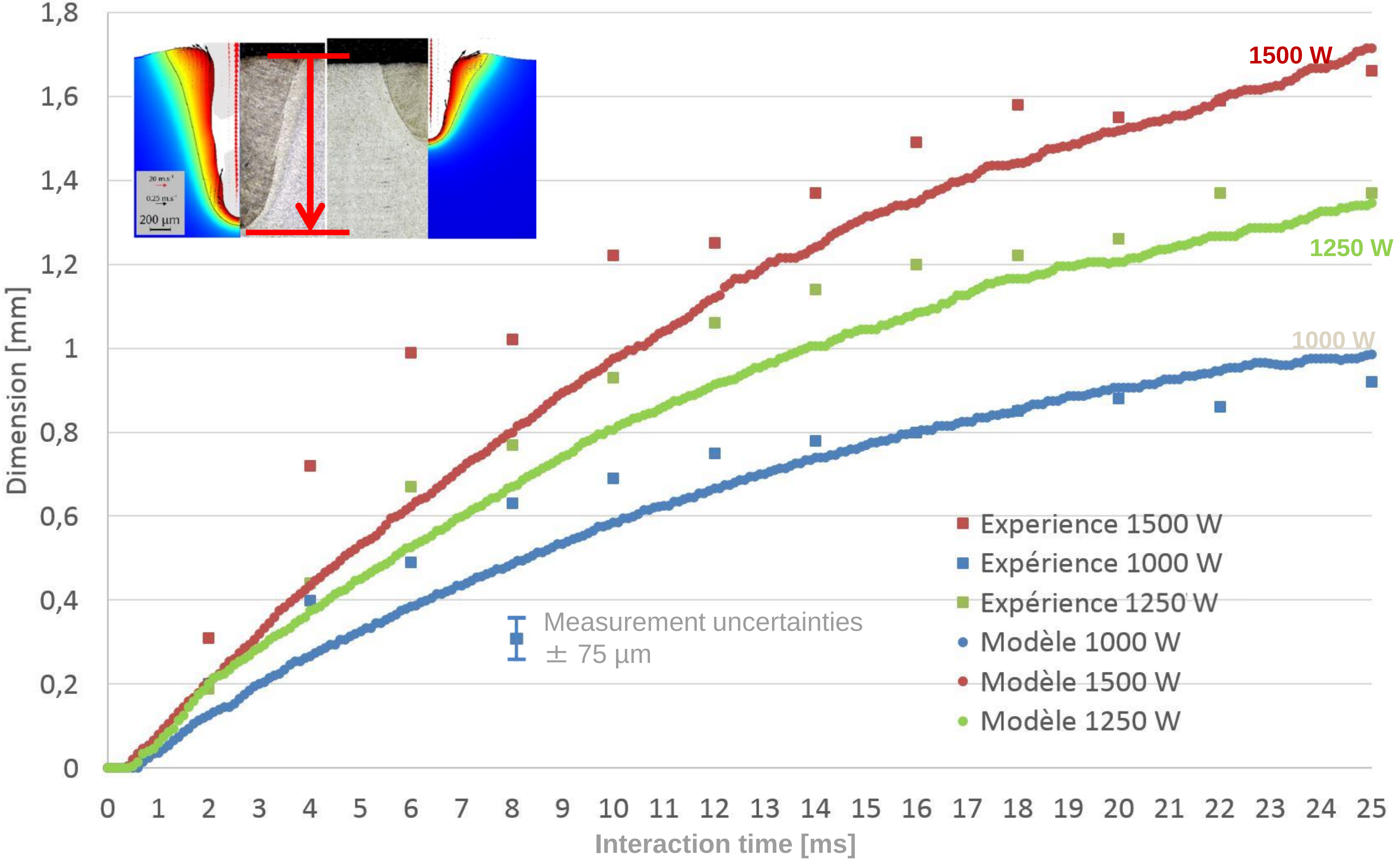




1000 W

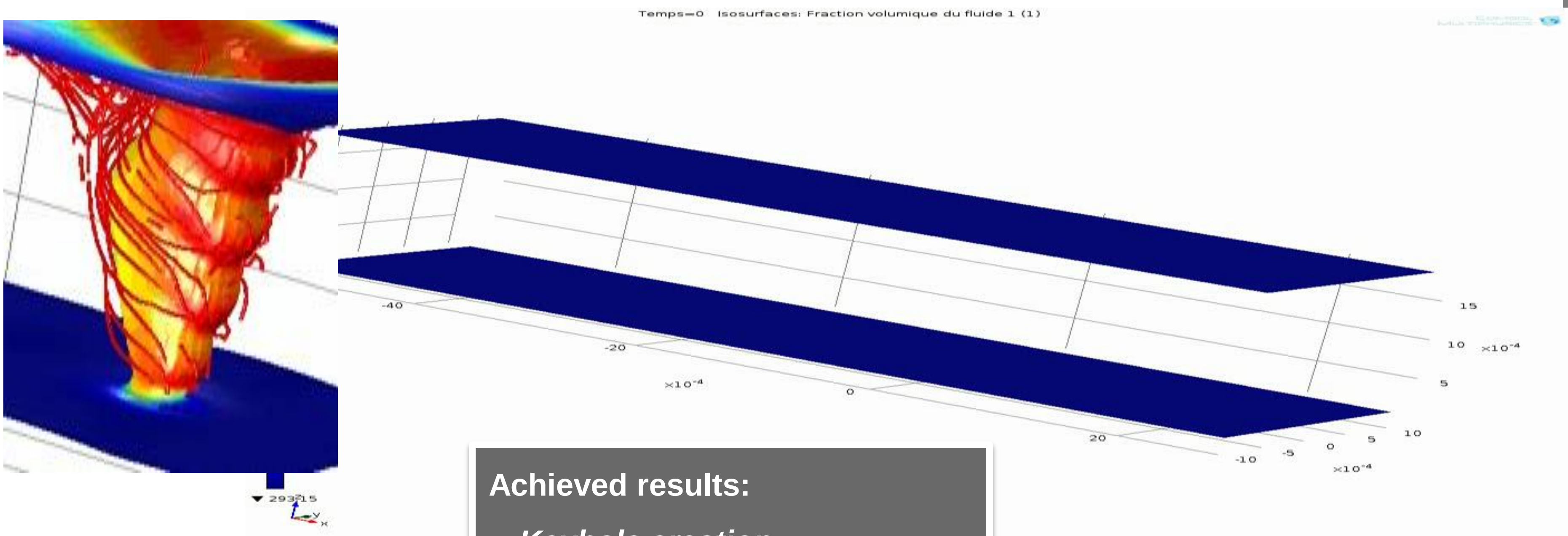
↑ Plaser → ↑ vaporization → ↑ depth & inclination of liquid → ↑ number of porosities

Model / experiment comparison :



Results in 3D : *(without electromagnetism)*

Case study - 4 kW – 6m/min



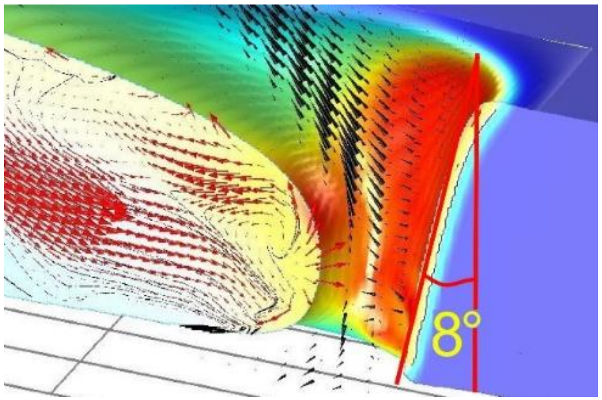
Achieved results:

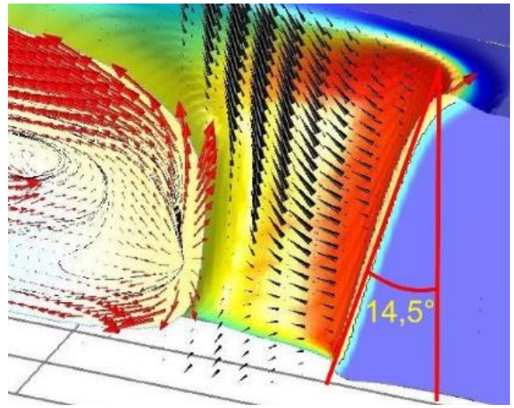
- ***Keyhole creation***
- ***Waves on the front wall***
- ***Keyhole inclination and stable***
- ***Melt pool growing***

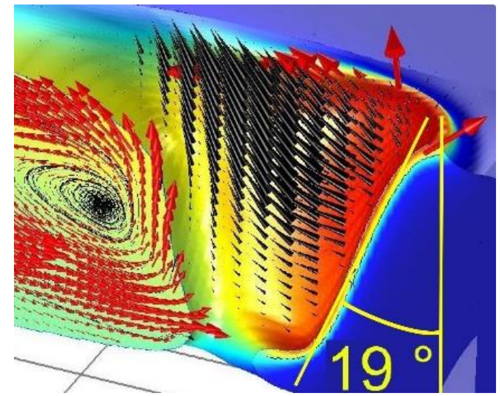
but:

- Waves at the solid surface

Capillary inclination, variation with forward speed: P_{laser} = 4 kW

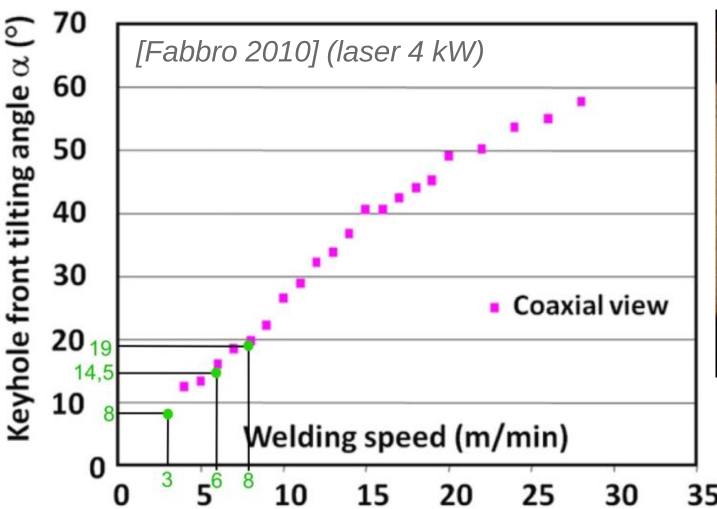


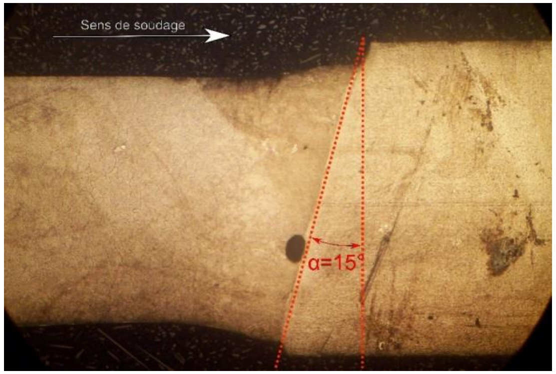




3 m/min ➡ 8° | 6 m/min ➡ 14,5° | 8 m/min ➡ 19°

(Speed) *(Calculated inclination)*



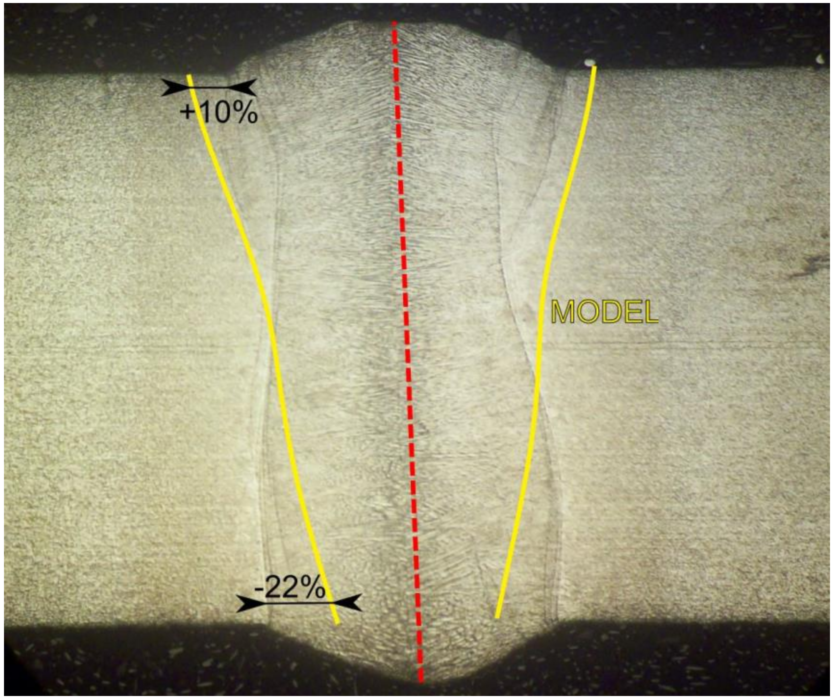


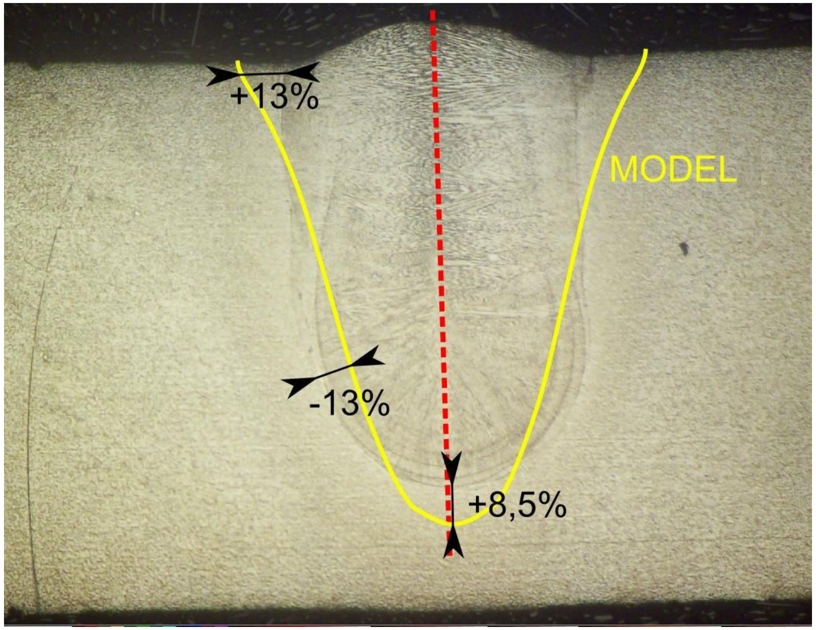
6 m/min ➡ 15°

➡ Good agreement model / literature

➡ Energy deposition coherent

Transversal cut (DP 600 steel, h=1.8 mm, P_{laser} = 4 kW)



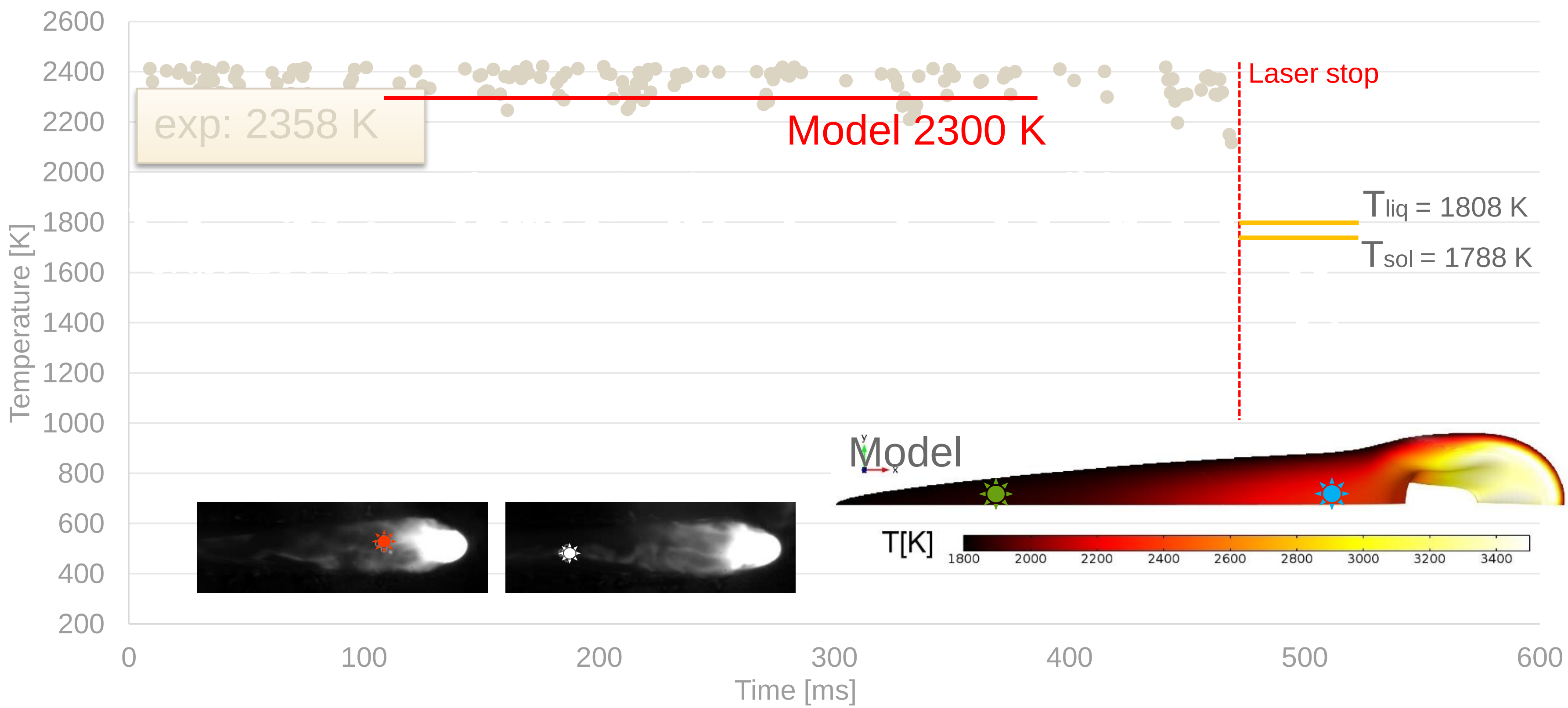


Melted surfaces equivalent (model vs cross section) → Energy deposition correct

→ **Partial penetration (or fully) predictable**

Monoband pyrometry → **Liquid surface temperatures** (Measurements: lab

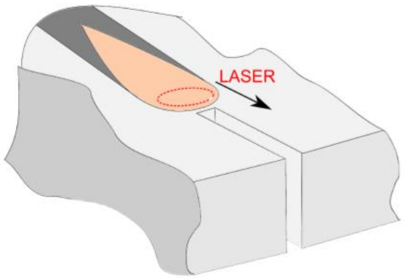
Camera : 10000 i/s; filtered 800-950 nm



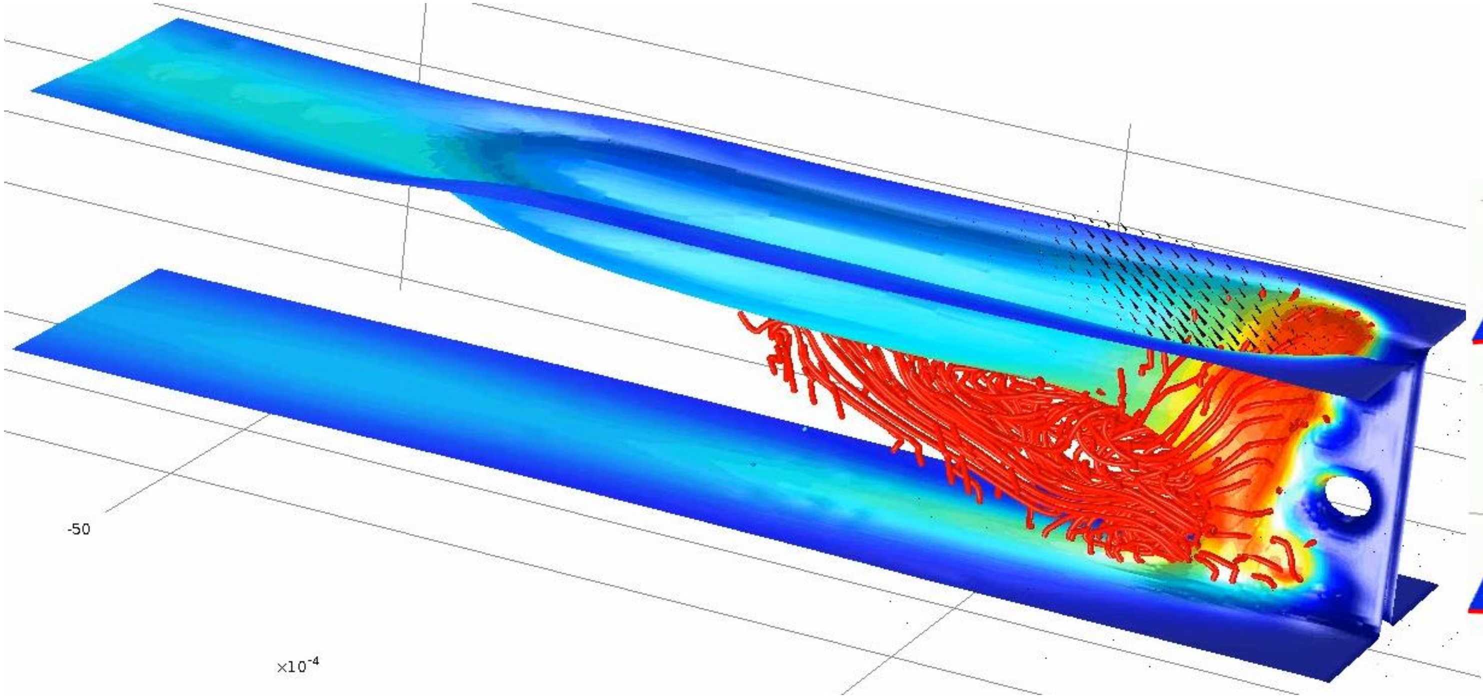
Conclusion : Accordance model-experiment excellent. Error < 6%

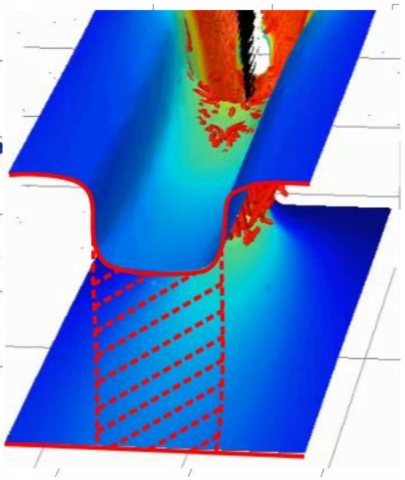
Welding with gap *(200 µm) :*

Case study



Prediction of undercut geometry defect





Conclusions

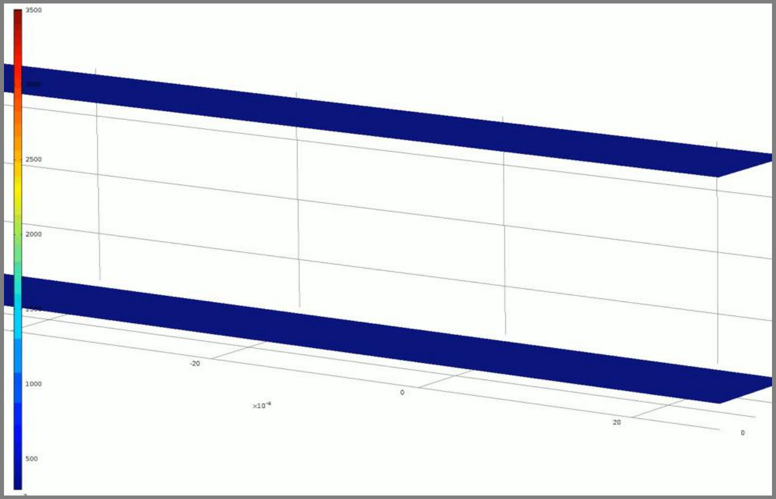
- **A Multi-physics simulation taking into account the main physical phenomena has been developed:**
  - **Keyhole generation, liquid collapsing, fluid flow in the melt pool**
  - **Inclination and oscillations of the front surface of the keyhole**
  - **Porosity behavior; partial/full penetration**

- **Experimental measurement and comparison with simulation:**
  - **Correct angle of inclination as a function of speed welding**
  - **Calculated temperatures in solid / liquid in good agreement with experience**

Challenges

- More realistic velocity in the vapor plume (modeling of steel evaporation)
- Reduce computation time (here 40 GB RAM and 8-12 cores => from 1 to 3 weeks)
- Modeling of the combination of three material states (liquids, solids & gases)

In collaboration with:



- Thanks for your attention -

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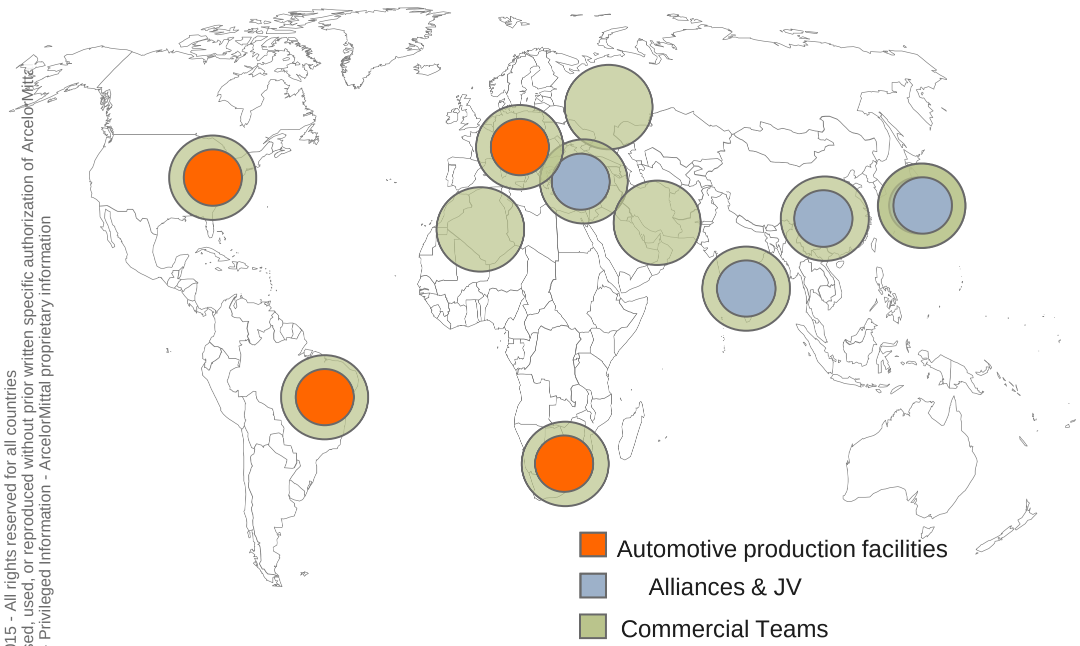
ArcelorMittal: Leader in Steels for Automotive

ArcelorMittal's industrial and commercial network

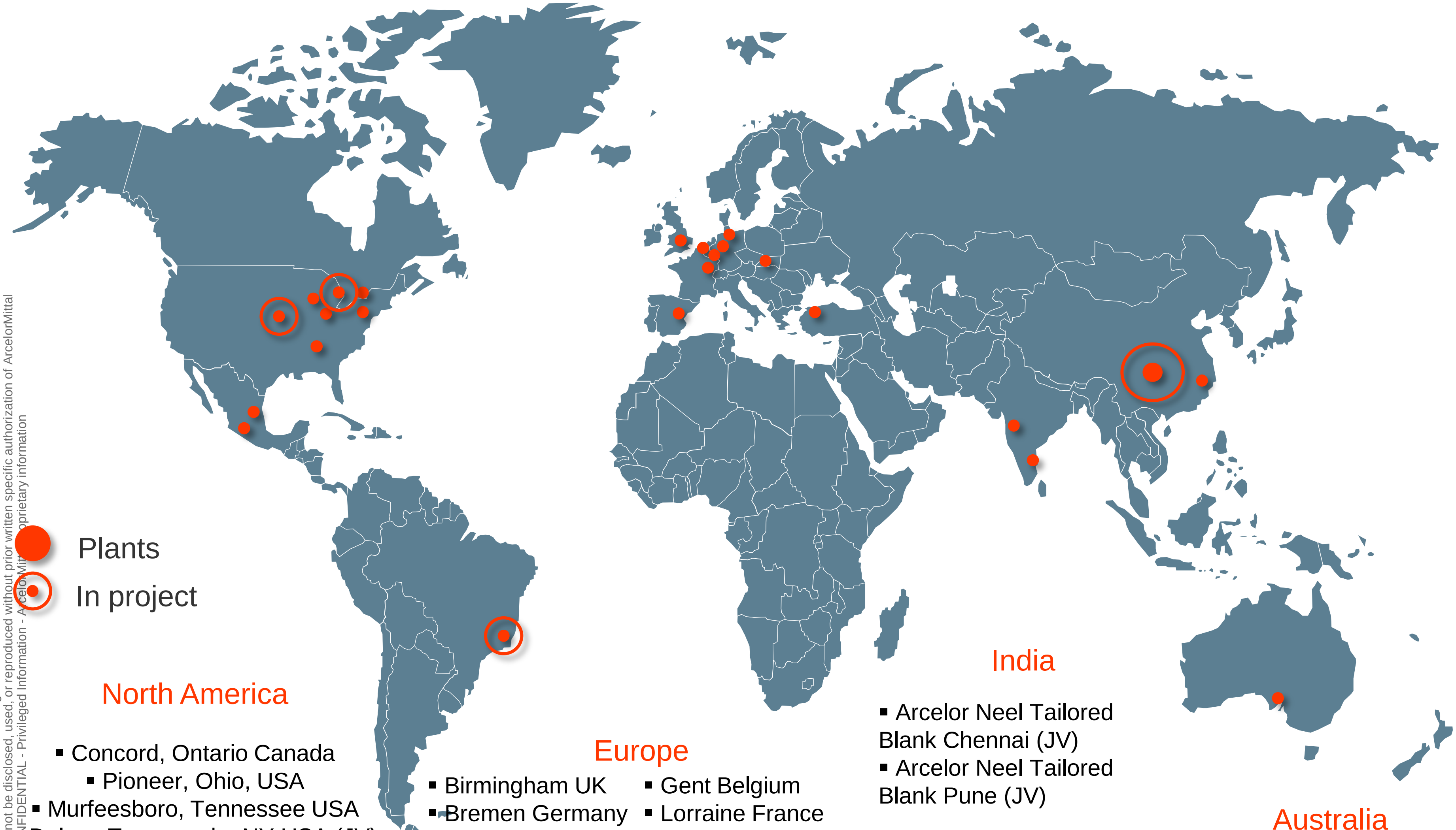


- Global automotive manufacturing presence (own facilities, alliances and JV)
- Proximity to the customer by global presence of commercial teams
- Global distribution network
- Unique product offerings to meet demand for safety, fuel economy and reduced CO_2 emission
- Strong investment in R&D

We are serving globally while developing industrial assets in emerging markets

ArcelorMittal Tailored Blanks Worldwide Presence

ArcelorMittal



North America

- Concord, Ontario Canada
- Pioneer, Ohio, USA
- Murfeesboro, Tennessee USA
- Delaco Tonawanda, NY USA (JV)
- Delaco Dearborn, Michigan USA (JV)
- Silao, Mexico
- San Luis Potosi, Mexico

Europe

- Birmingham UK
- Bremen Germany
- Neuwied Germany
- Liege Belgium
- Genk Belgium
- Gent Belgium
- Lorraine France
- Senica Slovakia
- Zaragoza Spain
- Orhangazi Tk (JV)

India

- Arcelor Neel Tailored Blank Chennai (JV)
- Arcelor Neel Tailored Blank Pune (JV)

China

Shanghai Baosteel & Arcelor Tailor Metal (JV)

Australia

ArcelorMittal Tailored Blanks Adelaide