ICB
Laboratoire Interdisciplinaire Carnot de Bourgogne

UBFC

ArcelorMittal

COMSOL CONFERENCE
2015 GRENOBLE

Modelling of Transport Phenomena in Laser Welding of Steels

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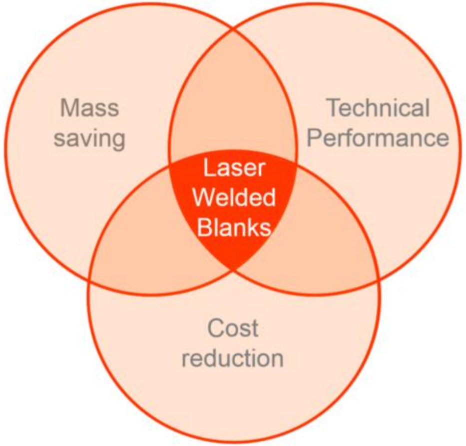
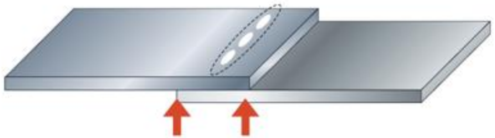
Laser Welded Blanks



Butt Joining > No overlap > Weight reduction



Overlap of approx. 20 mm

Butt laser weld line without any overlap

Thickness optimization (Best material at the best place) > Weight reduction

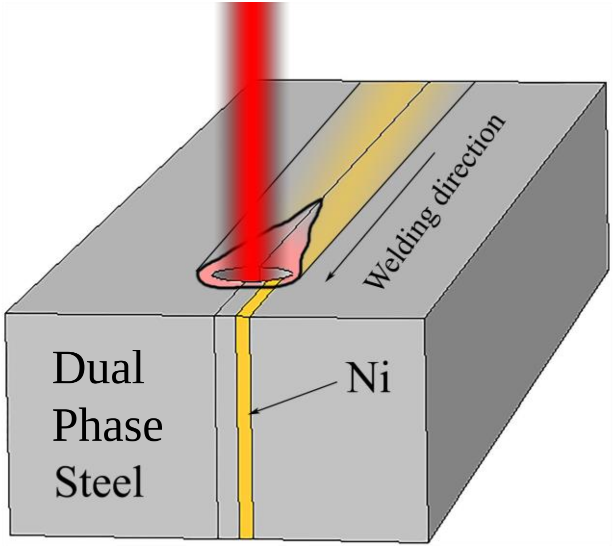
Problematic

Understand and control the mixing process in the weld between dissimilar steels

Multiphysical modelling of full penetrated laser welding

↑ *Validation*

Use of tracer material to validate convection paths (Ni)



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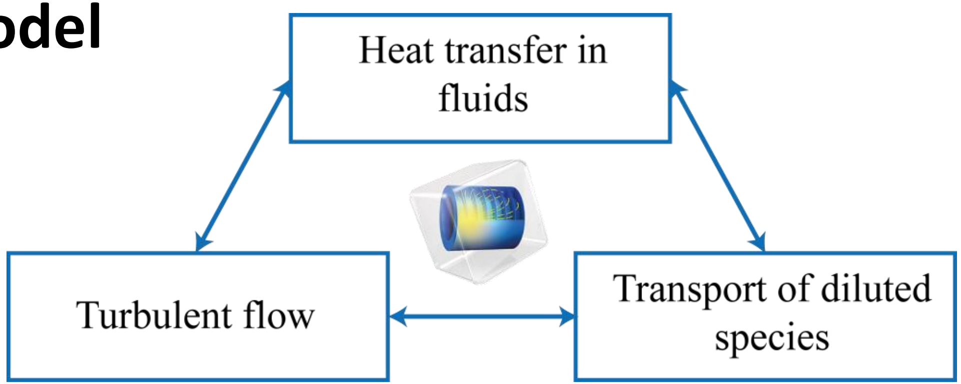
Model



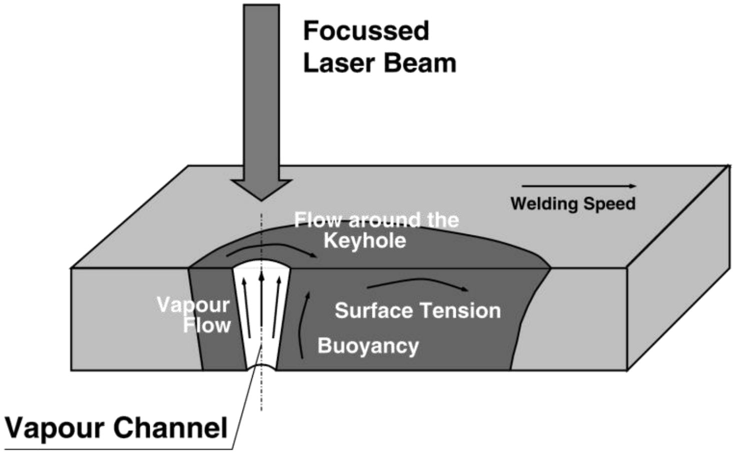
3D model

Pseudo-stationary formulation

Strong coupling

Taking into account of:

- Phase change
- Gravity
- Marangoni effect
- Vapour plume shear stress



Assumptions

Reduction of computational resources

Workstation

32 cores
128 GB RAM

- a steady keyhole with a conical geometry (full penetration)
- temperature inside the keyhole is assumed to be uniform

$$\left(T_{keyhole} = T_{vaporization}\right)$$

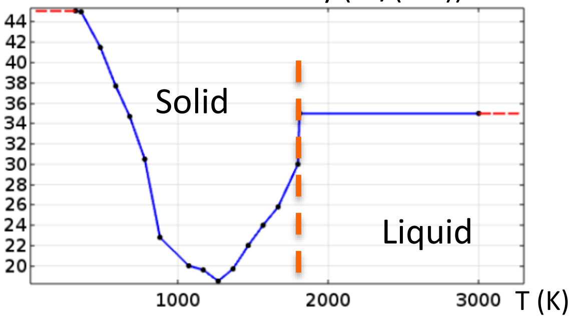
- top and bottom surfaces of the weld are assumed to be flat
- liquid metal is assumed to be Newtonian and incompressible

Material properties

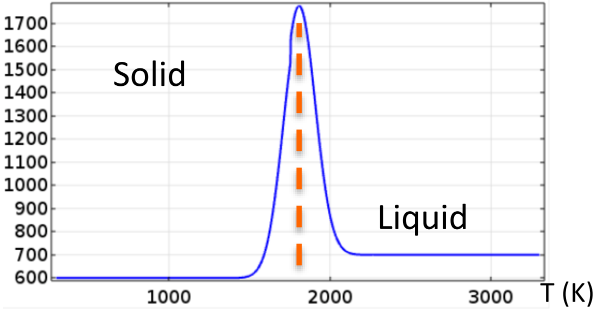
Thermal properties		
Fusion temperature	1808	K
Vaporization temperature	3300	K
Latent heat of fusion	2.7×10^5	$J \cdot kg^{-1}$

Uniform thermo-physical properties over all domain : 100 µm insert of Ni is neglected (T_f = 1728 K).

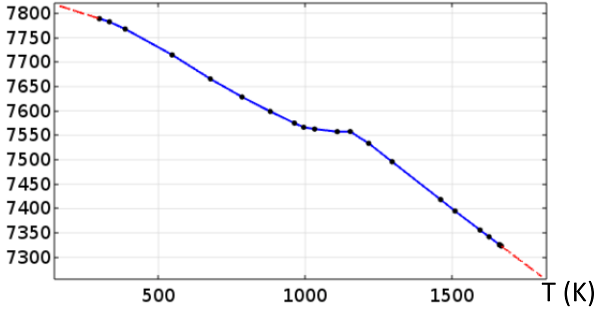
Thermal conductivity (W/(mK))



Heat capacity at constant pressure (J/(kg.K))



Density (kg/m^3)



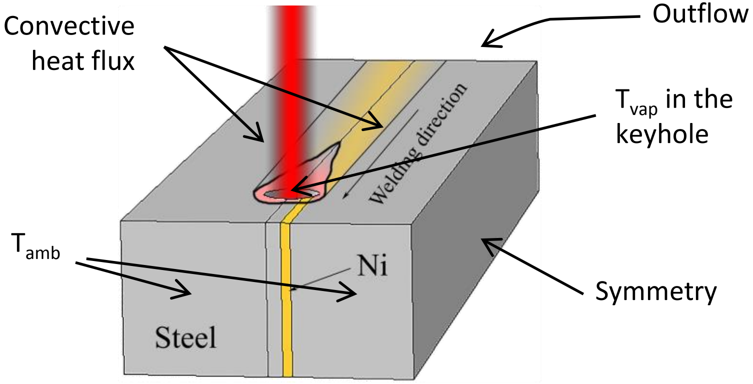
Heat transfer

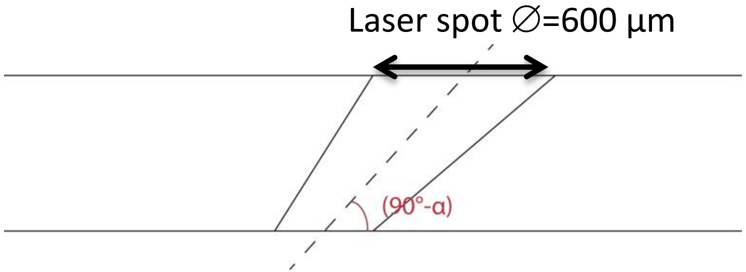
Energy equation: $$r C_p \mathbf{u}\cdot\nabla T + \nabla(-k\nabla T) = 0$$

$$C_p = C_p^*(T) + d \times L_{fusion}$$

$$d = \frac{1}{DT\cdot\sqrt{p}}\cdot e^{\left(\frac{T-T_{fusion}}{DT}\right)}$$

$$\alpha = k\cdot\frac{v\cdot d^2}{P}$$





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Reynolds-averaged Navier-Stokes Turbulent flow:

Wilcox modified k-ω model

Mass continuity:

$$r\nabla\cdot(\mathbf{u}) = 0$$

Momentum equation:

$$r(\mathbf{u}\cdot\nabla)\mathbf{u} = \nabla\cdot\left[-p\mathbf{I} + (m + m_t)\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right)\right] - r\mathbf{g} + F^{Marangoni} + F^{Plume}$$

$$F^{Marangoni} = \frac{¶g}{¶T}\times\frac{¶T}{¶t}$$

Turbulence cinetic energy:

$$r(\mathbf{u}\cdot\nabla)k = \nabla\cdot\left[\left(m + m_t s_k^*\right)\nabla k\right] + p_k - b_0^* r w k$$

Specific dissipation rate :

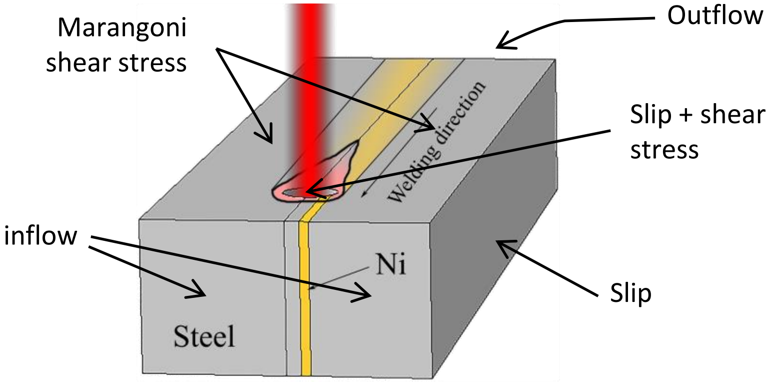
$$r(\mathbf{u}\cdot\nabla)w = \nabla\cdot\left[\left(m + m_t s_w\right)\nabla w\right] + a\frac{w}{k}p_k - r b_0 w^2$$

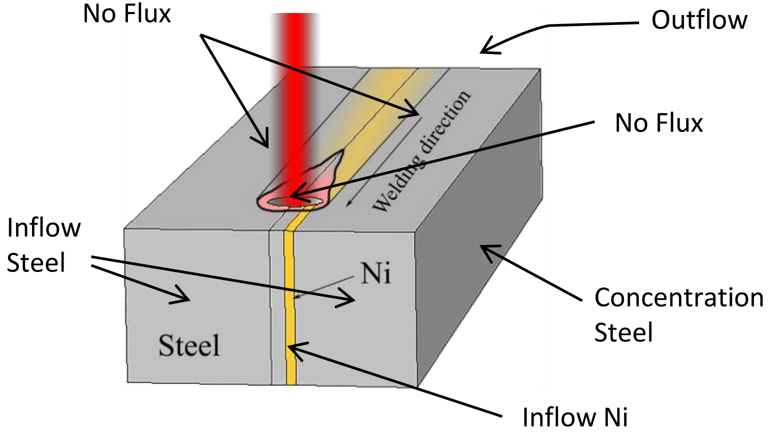
$$m_t = r\frac{k}{w} \qquad p_k = m_t\left[\nabla\mathbf{u}:\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right)\right]$$

Closure Coefficients :

α	13/25
σ_k^*	1/2
σ_ω	1/2
β_0	9/125
β_0^*	9/100
κ_v	0.41
B	5.2

Turbulent flow





Transport of diluted species

Fick's law: $\nabla \cdot (- D_i \nabla c_i + \mathbf{u} c_i) = 0$

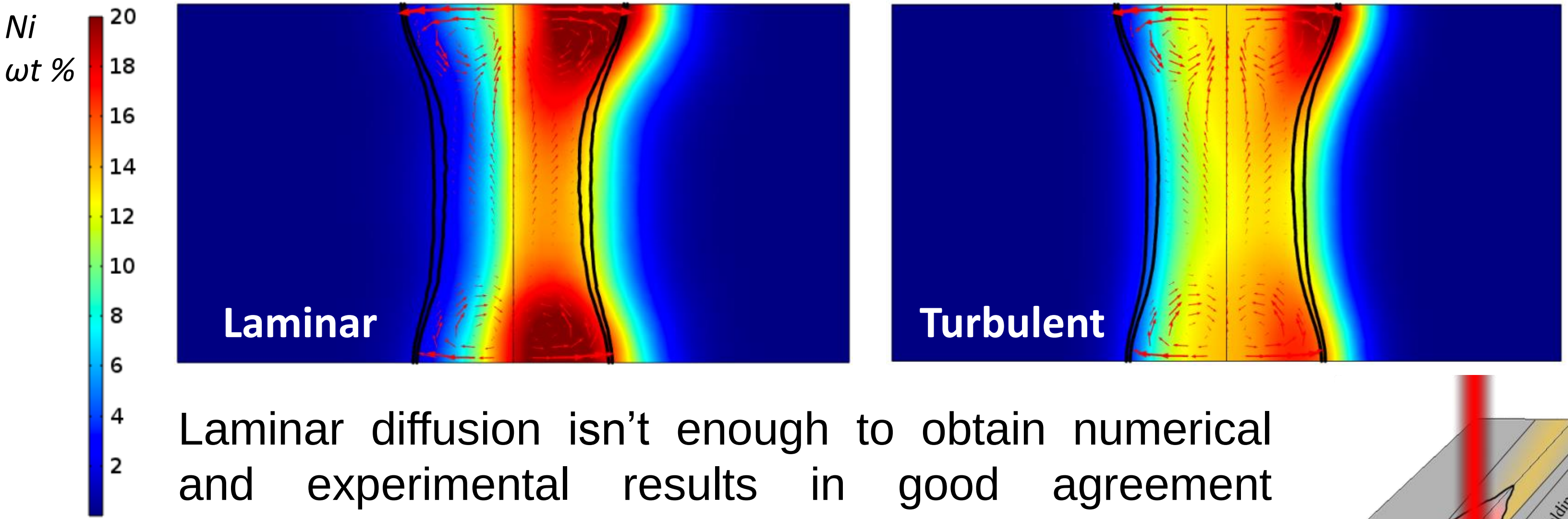
$$D_i = \frac{k_B T}{6 p r_i m} + \frac{n_T}{Sc_T}$$

Diffusion coefficient in liquid metal + turbulent diffusion

$$D_{Ni}^{T} = \left[3 \cdot 10^{-9} ; 6 \cdot 10^{-9} \right]$$

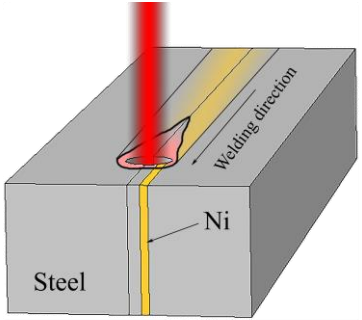
$D(T_{fusion})$ $D(T_{vap})$

Laminar flow ↔ Turbulent flow



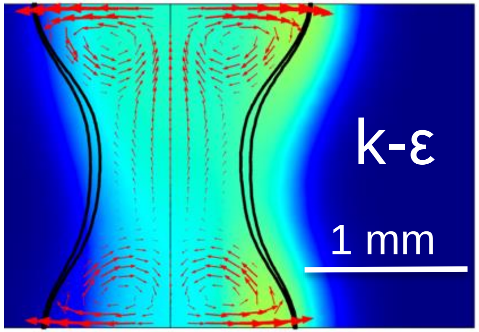
Laminar diffusion isn't enough to obtain numerical and experimental results in good agreement
Underestimation of mixing!

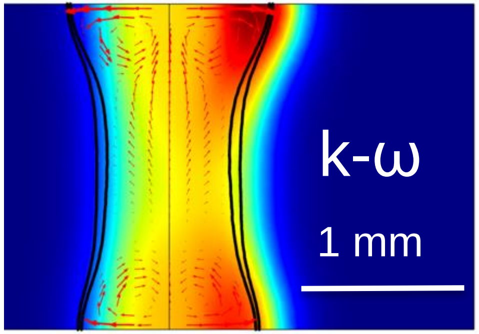
Turbulent mixing is essential to have an important exchange of matter between 2 vortexes.

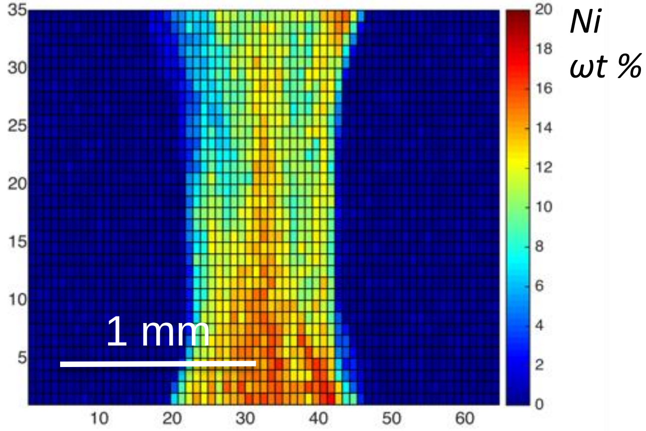


200 µm offset

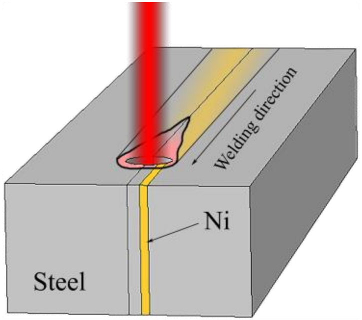
k-ε ↔ k-ω







Ni X-map

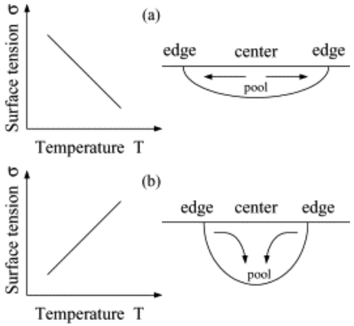


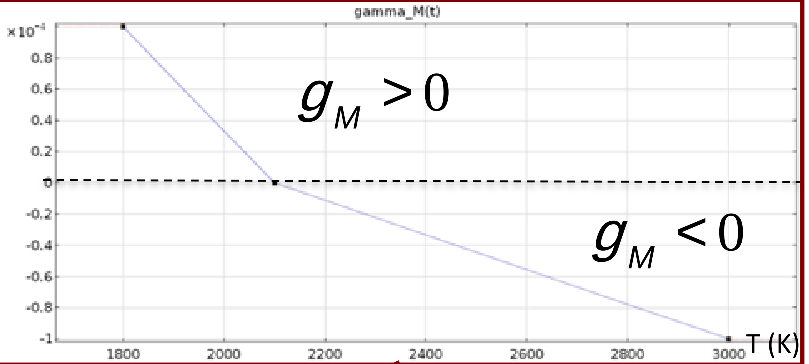
200 μm offset

k-ω model provides better agreement with experimental results

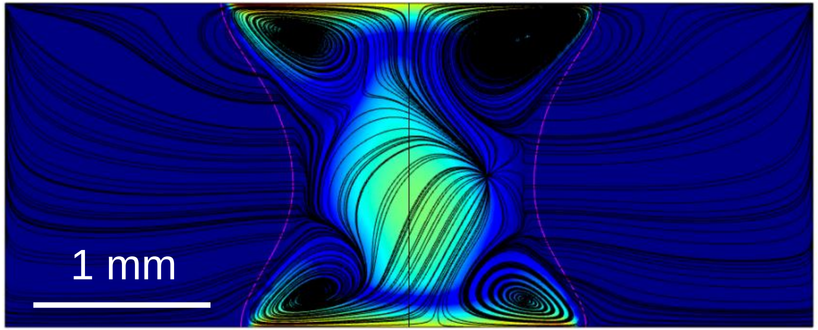
Marangoni effect

Marangoni convection and solid phase modelling

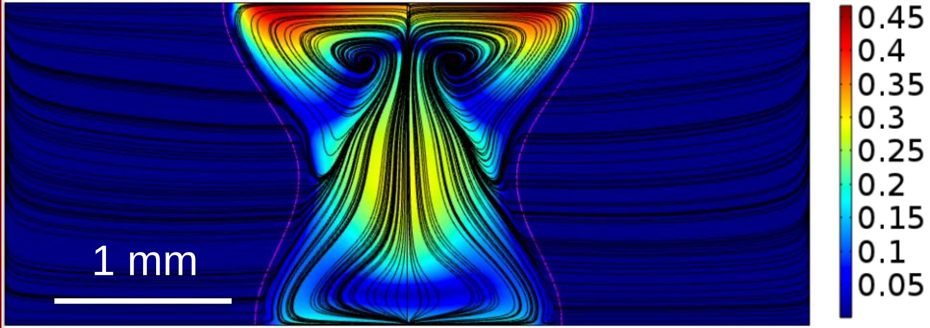




$g_M = -1 \times 10^{-4} < 0$



$g_M(T)$



Stream lines and velocity magnitude in cross section

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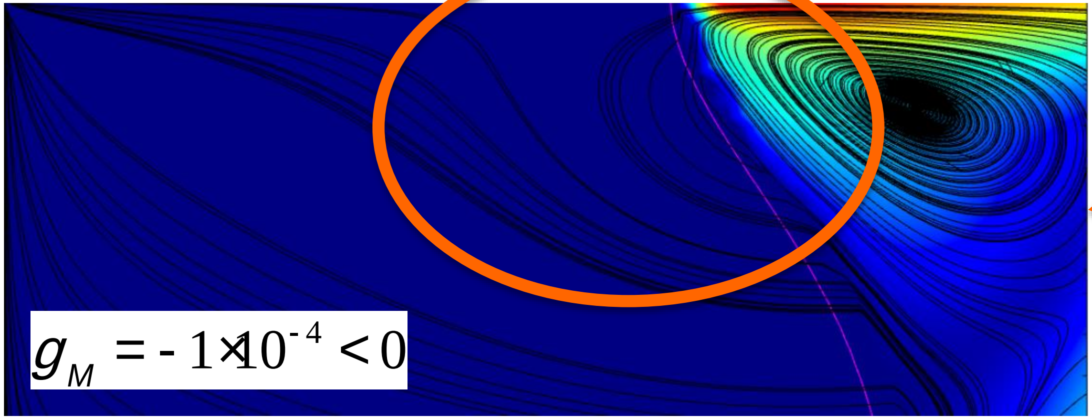
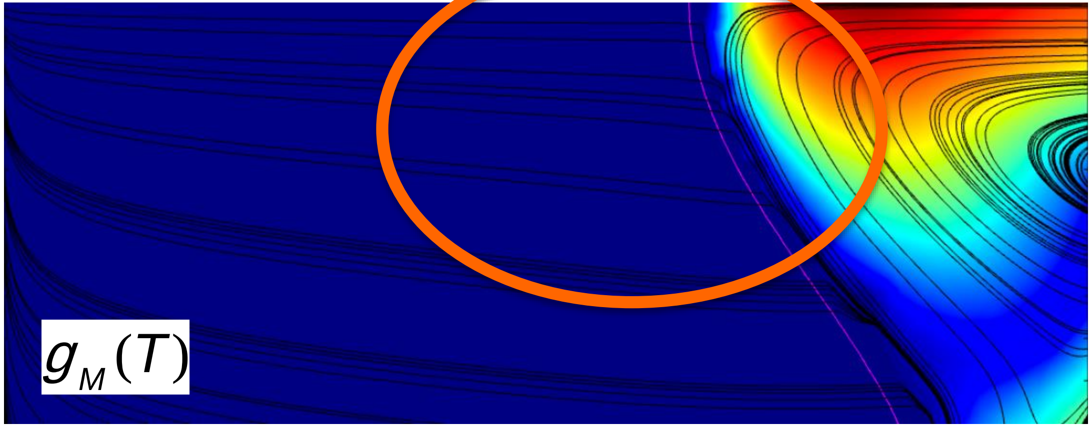


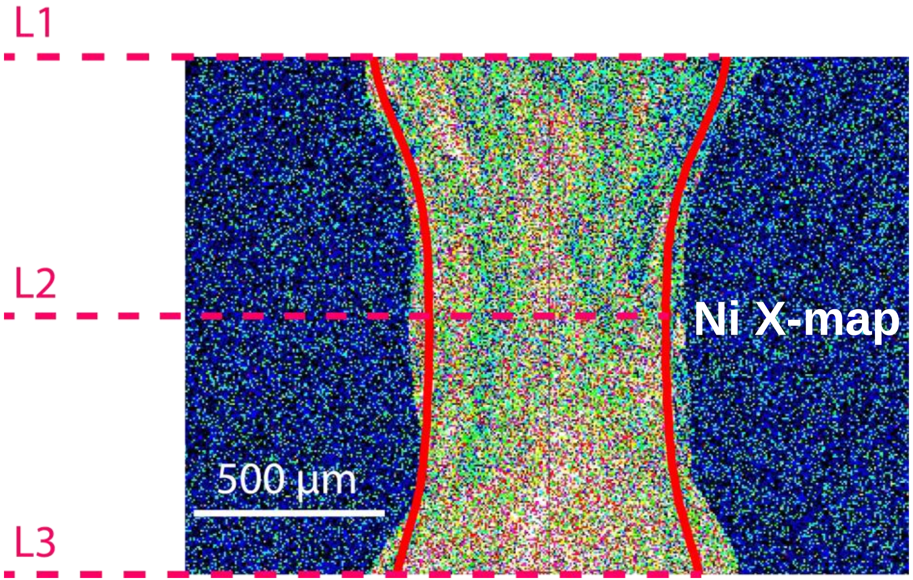
Liquid entering into solid



Weld geometry

$P = 4\ kW;\ Vs = 6\ \text{m.min}^{-1}$

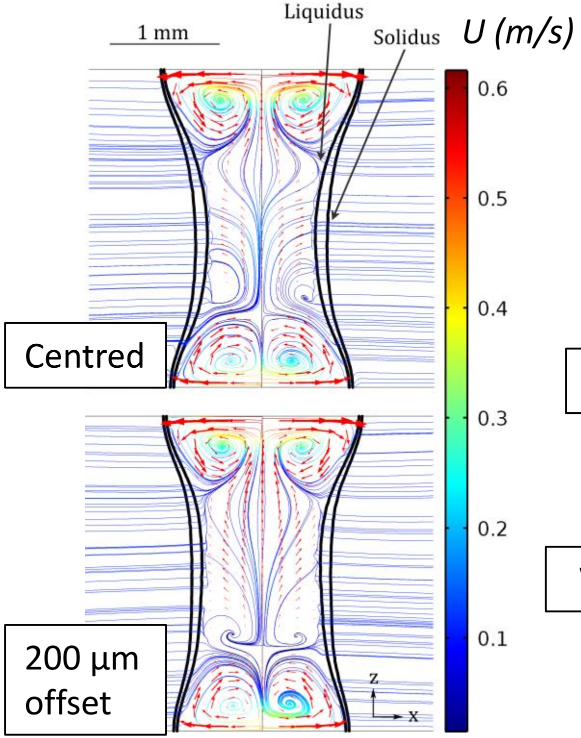
Dimensions (µm)		Laser offset (µm)	
		0	200
L1	Exp	858	1069
	Calc	935	884
	ε (%)	**9.0**	**17.3**
L2	Exp	659	758
	Calc	791	797
	ε (%)	**20.0**	**5.2**
L3	Exp	1033	945
	Calc	897	865
	ε (%)	**13.2**	**8.4**



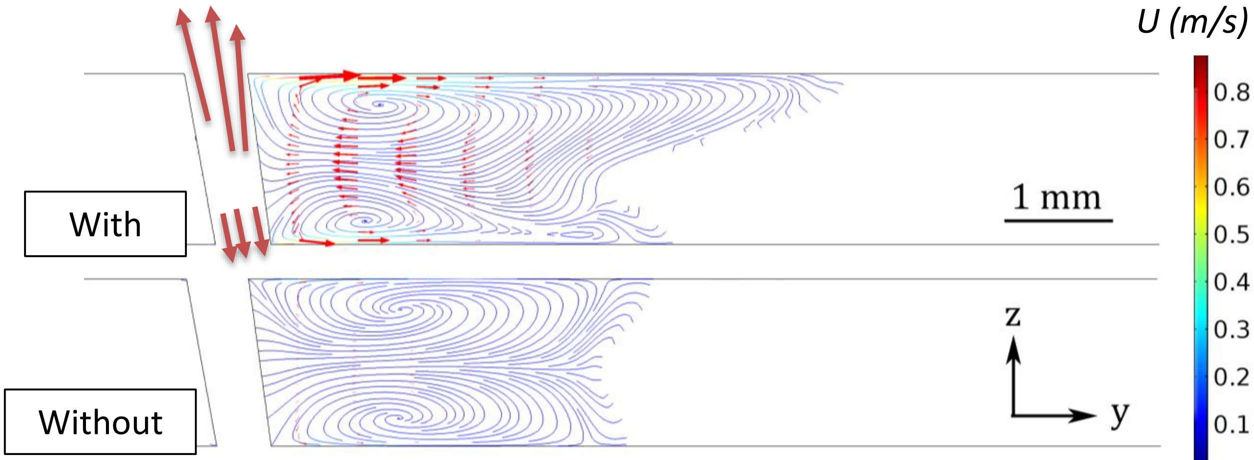
ε < 20 %

Centred laser position

Stream lines and velocity field



The maximum velocity is observed on top and bottom surfaces



Simulation with and without plume shear stress (200 µm offset)

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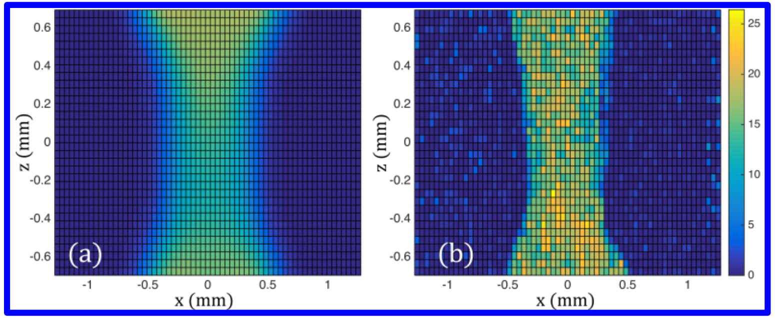
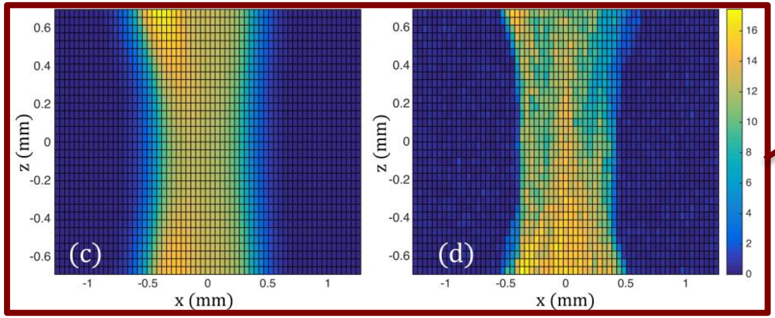
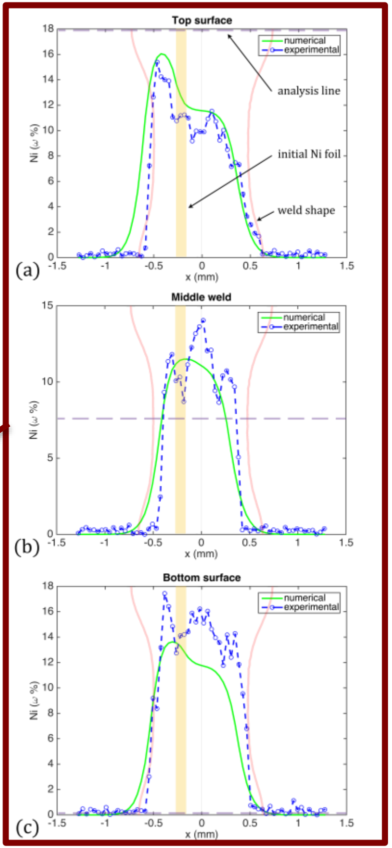
Nickel mass fraction in cross-section

centred — 200 µm off-set

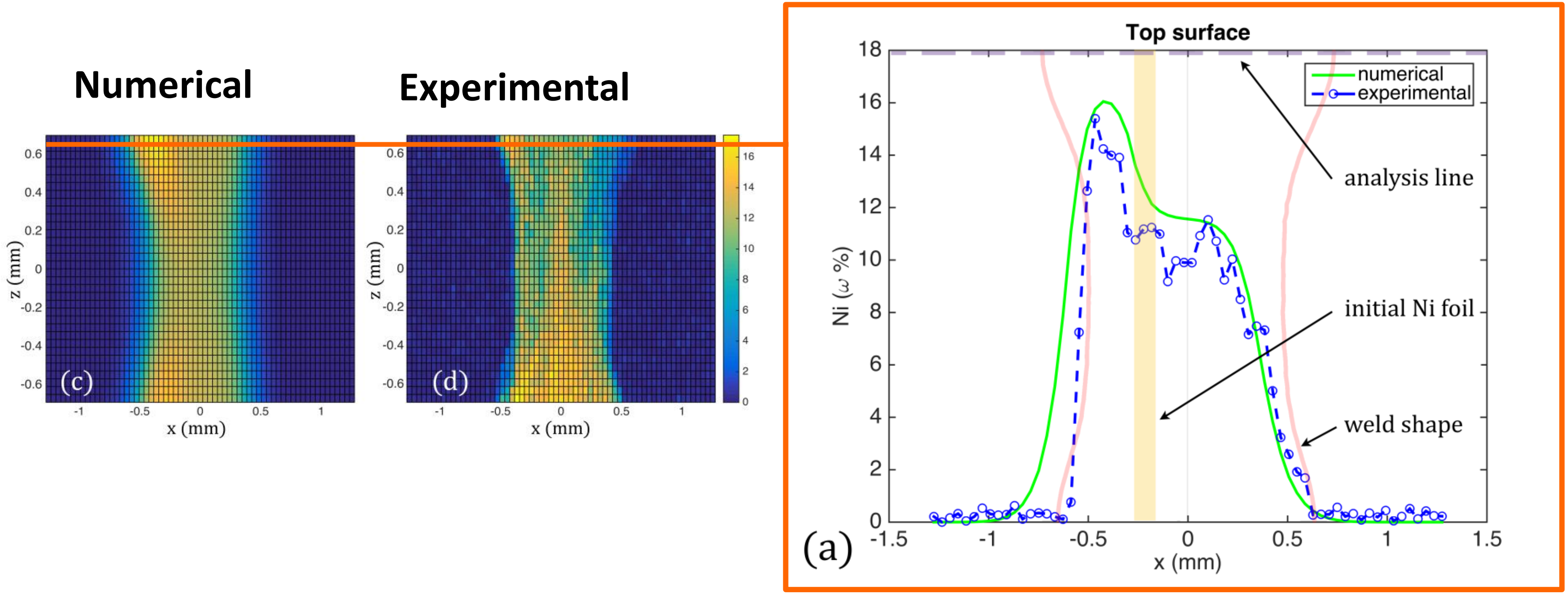
Numerical **Experimental**



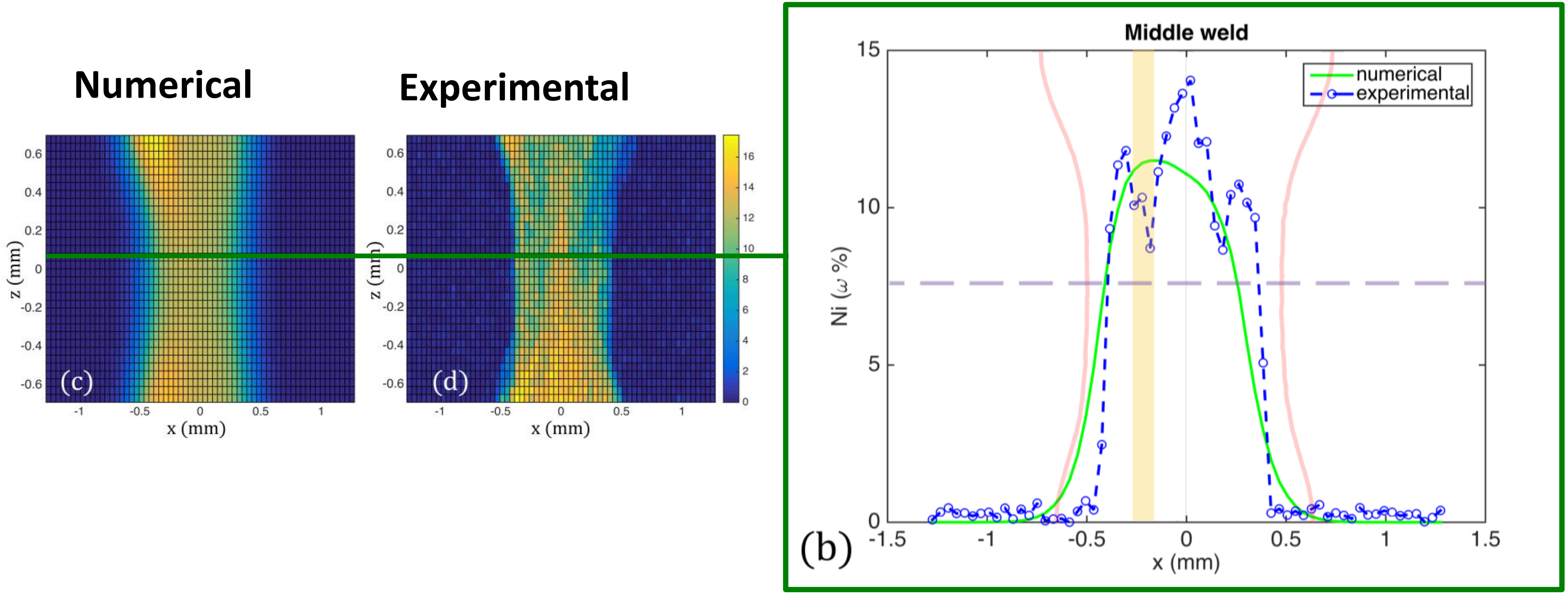




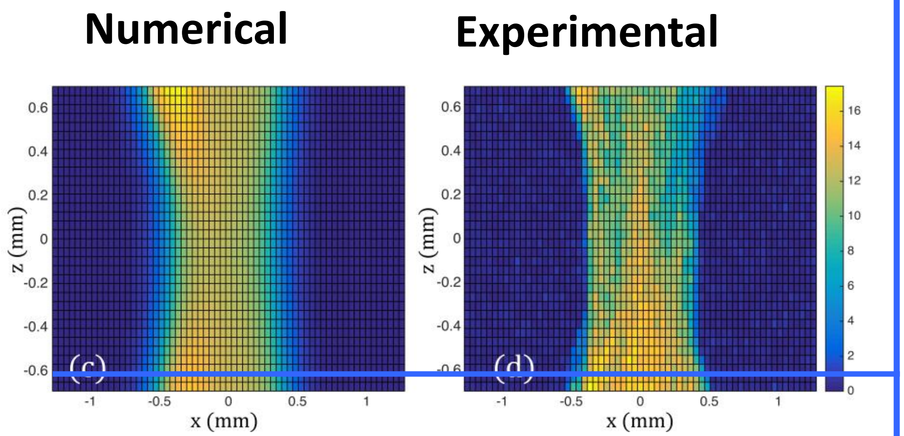
Nickel mass fraction in cross-section

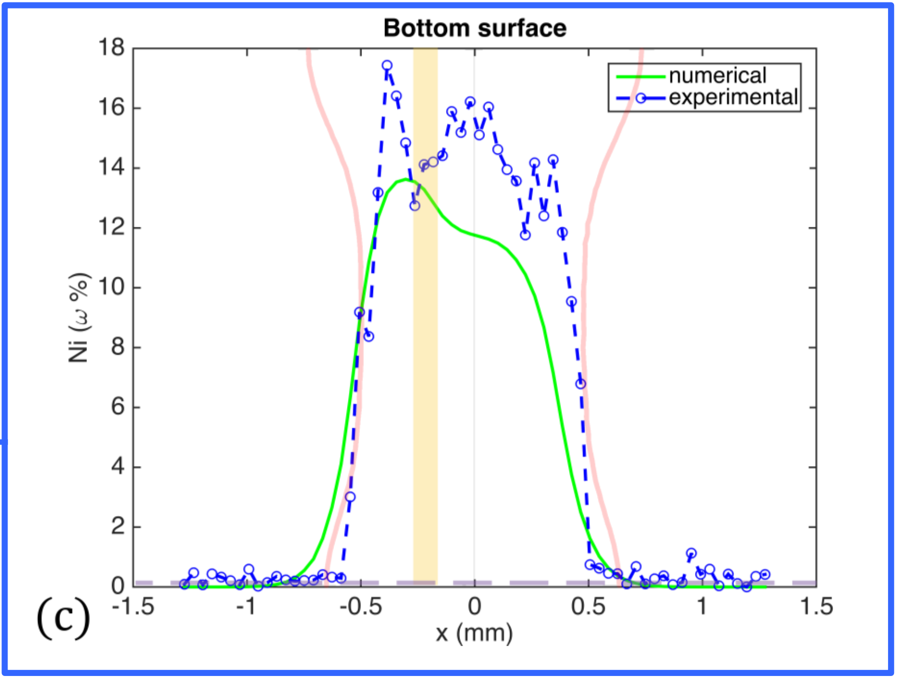


Nickel mass fraction in cross-section



Nickel mass fraction in cross-section



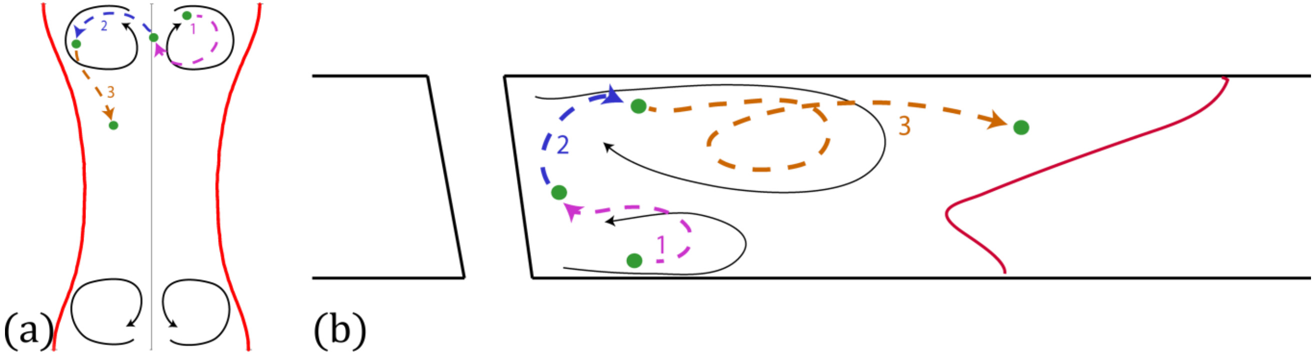


Conclusion

Model predics macroscopic chemical composition in the laser weld between dissimilar steels

- Turbulent Mixing
- Convective Mixing
- Macroscopic scale

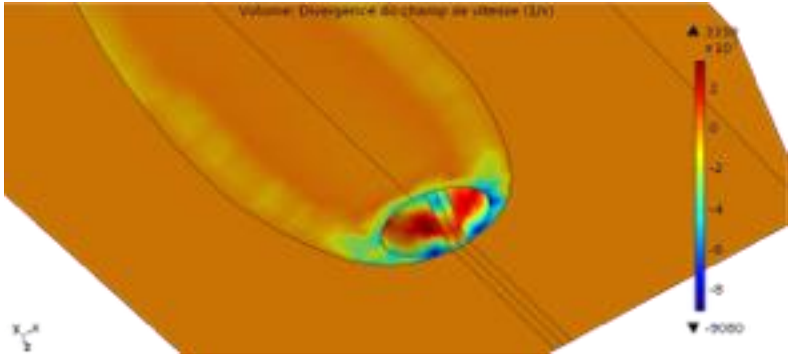
- Good agreement of the weld geometry
- Modelled convection paths validated with Ni tracer
- **Next step** : Welding dissimilar steels

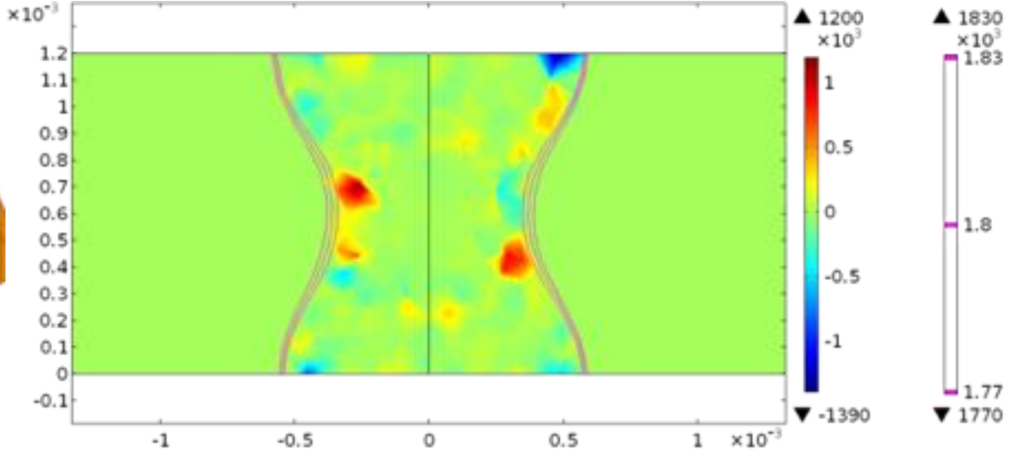


Prospects

In front of the keyhole and in the mushy zone, the velocity field divergence **isn't calculated well**.

- Fix it …





Bad calculation of U divergence!

THANK YOU FOR YOUR ATTENTION!