3D simulations of Marangoni-driven free surface flows, applied to laser polishing processes

SALON INTERNATIONAL
LEADER DE LA HAUTE PRECISION
HORLOGERIE-JOAILLERIE · MICROTECHNOLOGIES · MEDTECH

SWISS PHOTONICS

Photonics 4
intelligent processing

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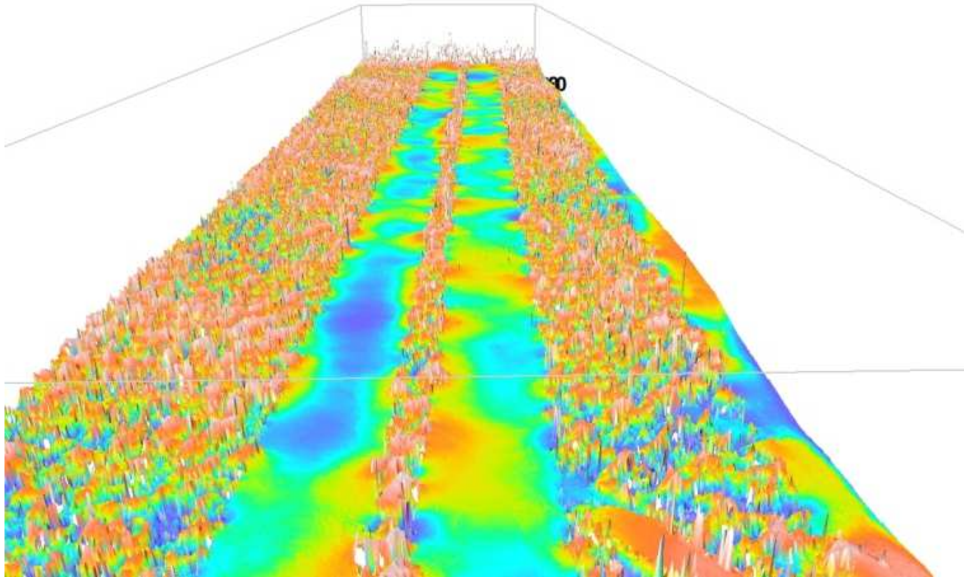
CTI Project 25363.1 PFNM
Shallow Laser Surface Melting (SLSM) for mould industry

Outline

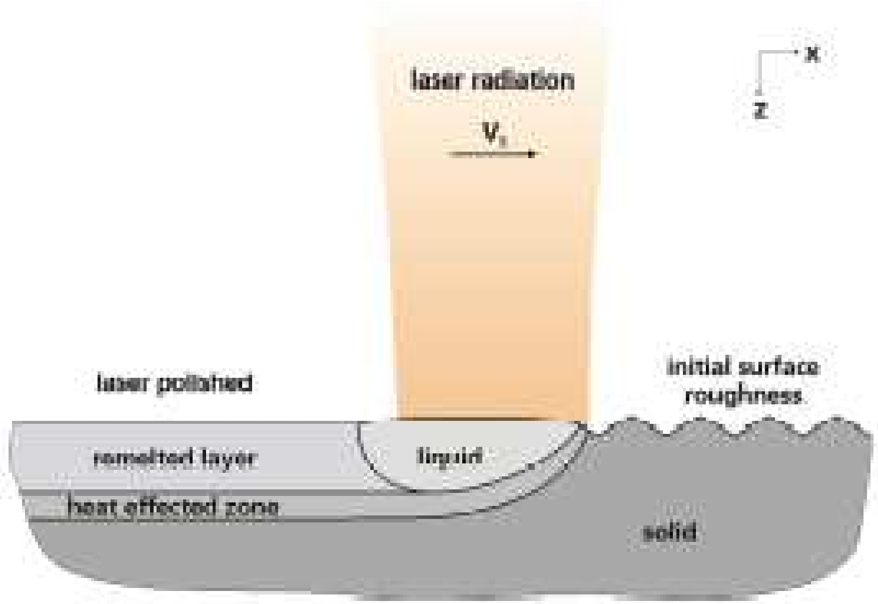
- **Introduction**
- **Simulation principle and software**
  - **Simulation of laser treatment process**
  - **Simulation software (*polishing3d* and *cfsFlow*)**
  - **Material properties (surface tension vs temperature)**
- **Simulation results and comparisons with experimental results**
  - **Where is the laser spot with respect to the melt pool?**
  - **Influence of the surface tension terms – Simulation results**
  - **Influence of surface tension coefficients – Simulation results**
  - **Influence of the surface's waviness - Simulation results**
- **Conclusions about simulations for this process**
- **Acknowledgments**

Introduction

- **Surface re-melting is a part of the laser polishing process.**
- **The rough surface of the material is melted by a laser radiation. In the liquid state, influence of surface tension affects the resulting quality of the surface. The normal part of surface tension tends to maintain a flat surface. The Marangoni effect, on the other hand, can lead to an increase of the surface roughness.**
- **Simulation of the laser polishing process allows to highlight qualitatively the physical parameters involved in this type of treatment and their influences.**



Surface topography with 2 re-melted lines, in the center (EMPA 2018 – Bastian Meylan)



Temmler A, Willenborg E, Wissenbach K. Laser polishing. 10.1117/12.906001

Simulation principle and software

Simulation of laser treatment process

- **To achieve the simulation of laser treatment process, it's necessary to solve the thermal aspects including phase transition and variation of physical properties with respect to the temperature, and also the aspects of fluid dynamics related to the melting pool movements due to convection.**

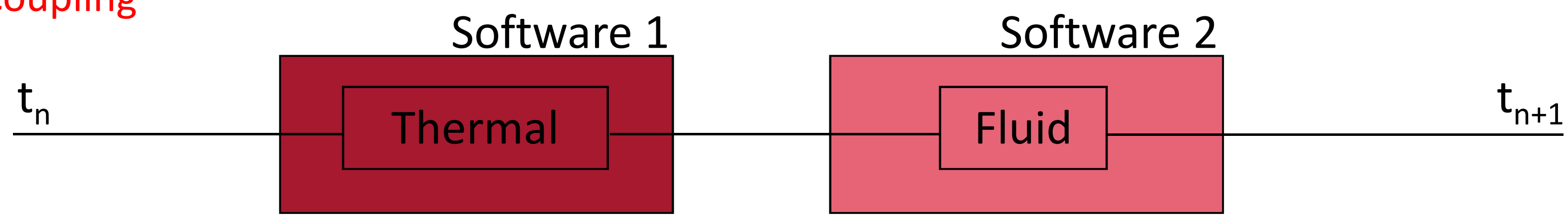
- **In this project, two software are used:**
  - ***polishing3d*** software to solve the thermal problem (developed by Prof. Eric Boillat (EPFL STI IMX LMTM)).
  - ***cfsFlow*** (complex fluid surface Flow) software to solve the CFD problem (developed in the Group of Prof. Marco Picasso (EPFL SB MATH GR-PI)).
  - **Coupling between the two software and additional developments for this specific type of problem.**

- **Difficulties to simulate such a process:**
  - Multi-physical problem.
  - Difference between the scales of the physical phenomena.
  - Importance of the physical data of materials.
  - Lack of experimental results, especially for the velocity in the melt pool.
  - Difficulties to observe all phenomena in real situations.

Simulation of laser treatment process

- **About coupling methods (e.g. coupling thermal/CFD)**
  - Strong coupling

  - Weak coupling

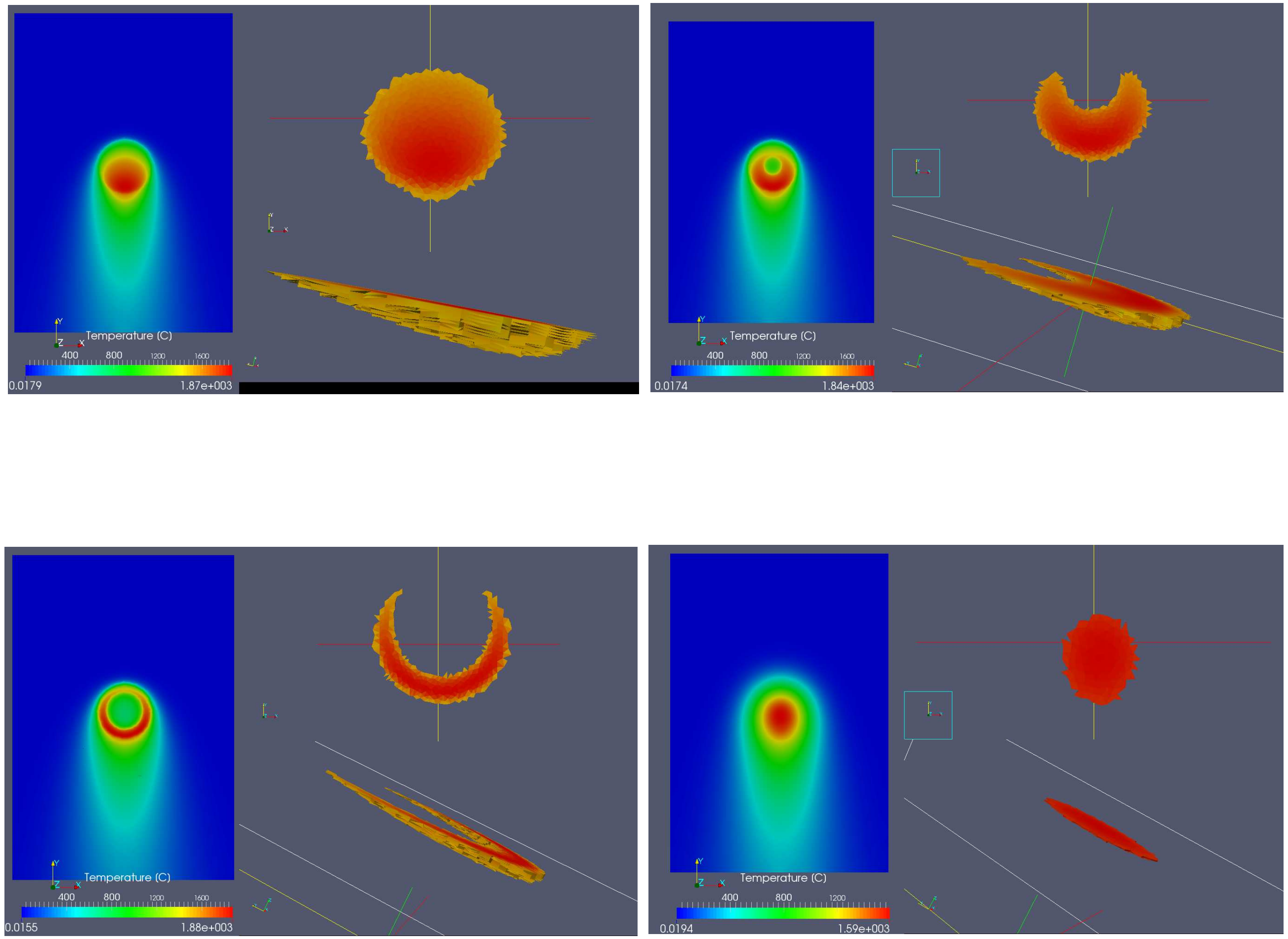


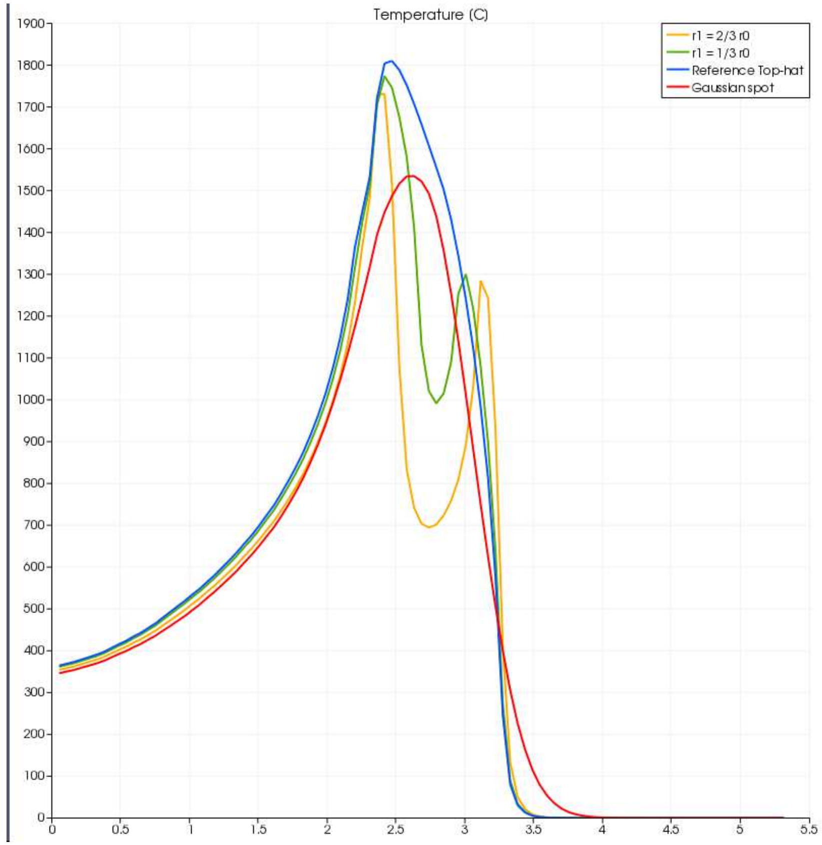
  - Interaction between solutions:
    - The temperature field (enthalpy) influences the physical properties (ex.: surface tension)
    - The velocity field influences the thermal problem (geometry change + convection)
  - With the weak coupling approach, the temperature field affects the CFD problem, but the resulting velocity field has no effect on the thermal problem:

Conclusion: with this approach, it is possible to completely solve the thermal problem (in time) before solving the fluid flow induced by the temperature gradient (convection) - extrapolation of the thermal solution (for rough surfaces)

Simulation of the thermal problem (*polishing3d*)

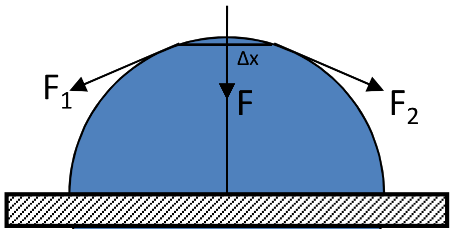
- **Ex. Study using ring spot instead of round laser spot**



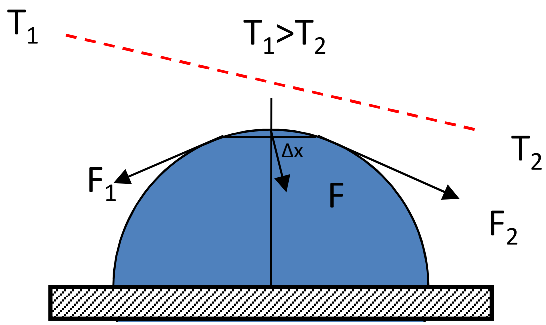


Simulation of the CFD problem (cfsFlow)

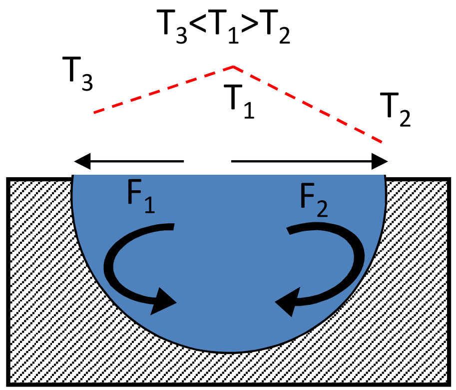
- **This software is dedicated to CFD (computational fluid dynamics) with some additional modules**
- **Surface tension and Marangoni force**
  - Implementation of Marangoni force
    - This force is induced by the temperature gradient
    - Depending on the used model, this force is added to the surface tension term or the model allows to directly integrate the surface tension variation.
  - Physical idea:



Non hydrophilic and non hydrophobic drop (without Marangoni effect)



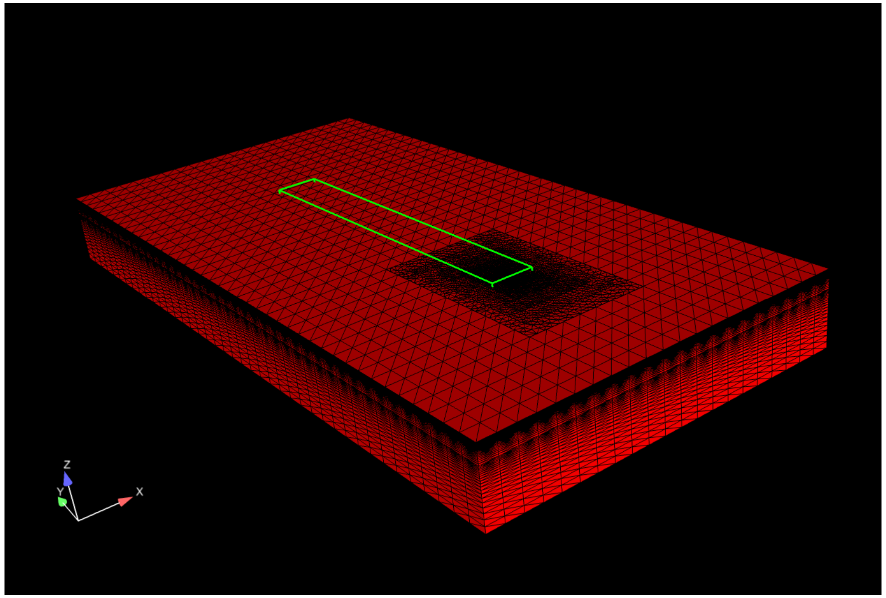
Non hydrophilic and non hydrophobic drop (with Marangoni effect)



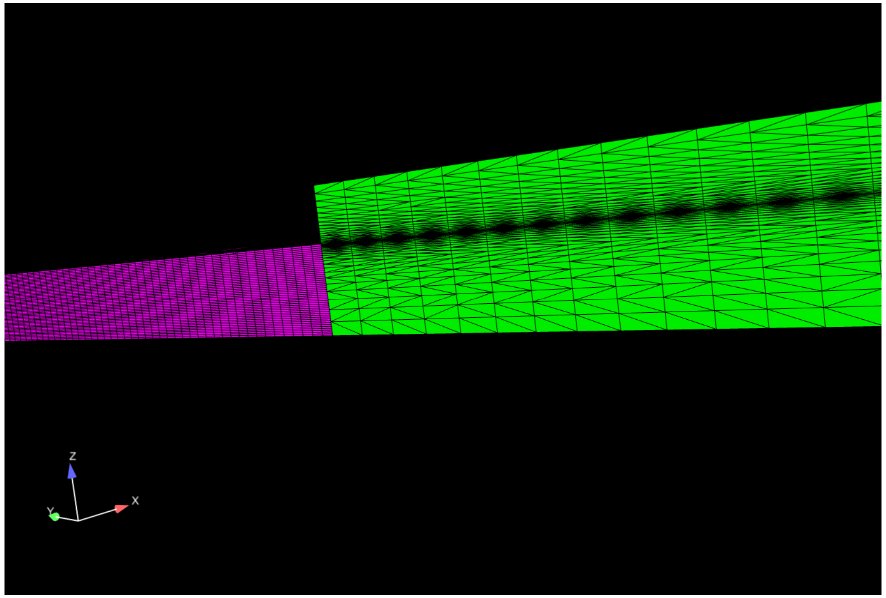
$F_1=F_2$ The resulting force is radial	$F_2>F_1$ The resulting force is no longer radial	The melt pool is dragged away by the Marangoni force

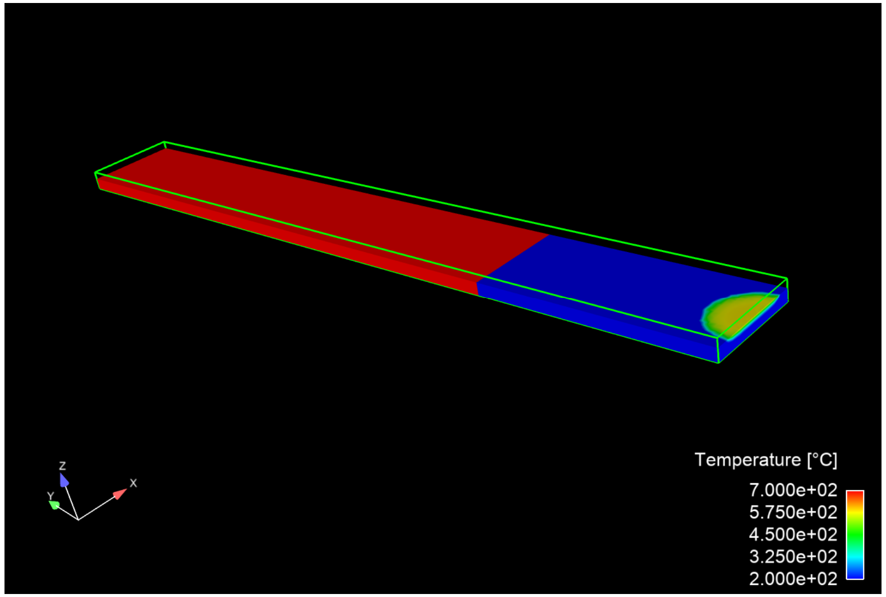
Simulation of the CFD problem (*cfsFlow*) 2/3

- **Works done and developments**
  - Interpolation – extrapolation "module" creation
    - Mesh reading
    - Temperature field reading
    - Interpolation between domain intersections
    - Extrapolation outside
  - Example :



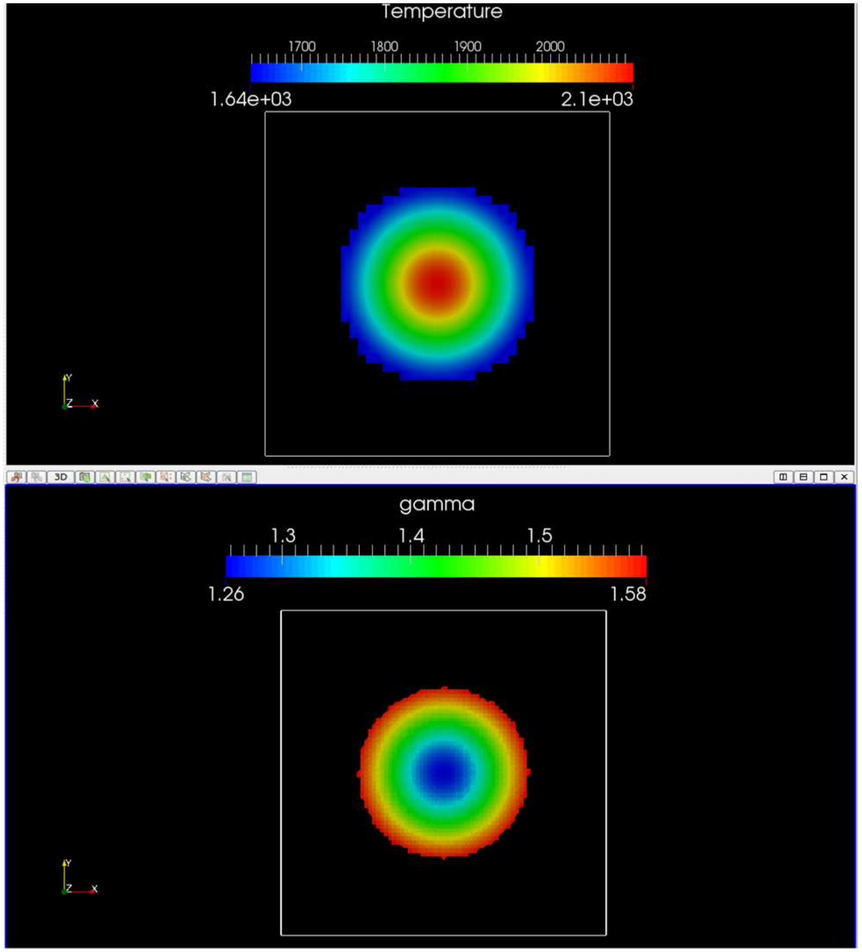
Note: Use of parallel interpolation (MPI). External tools

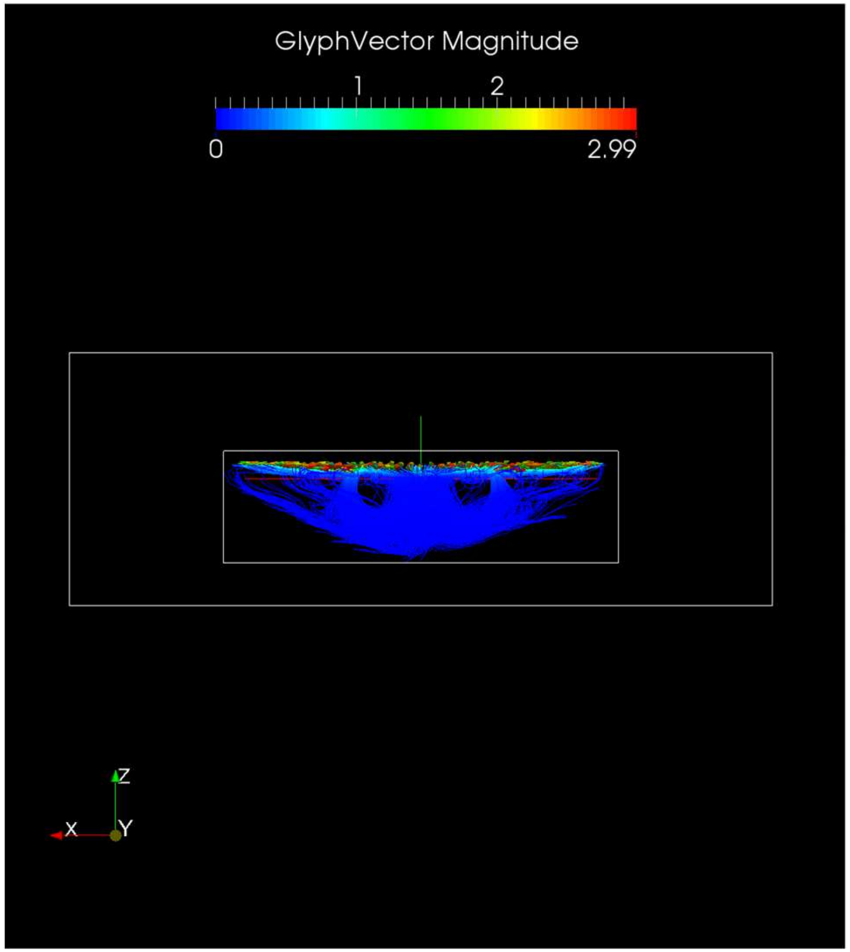




Simulation of the CFD problem (*cfsFlow*)

- **Example of results (academic test)**

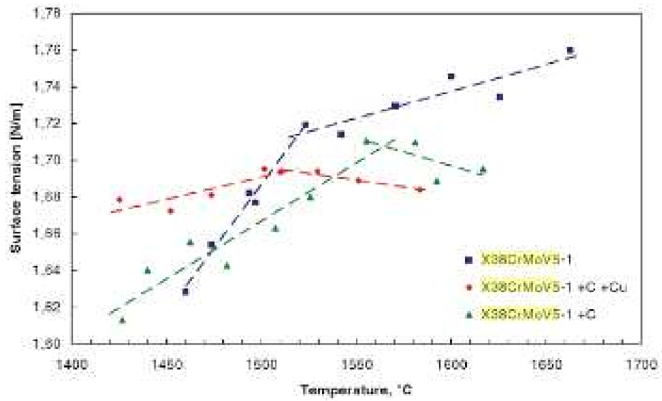




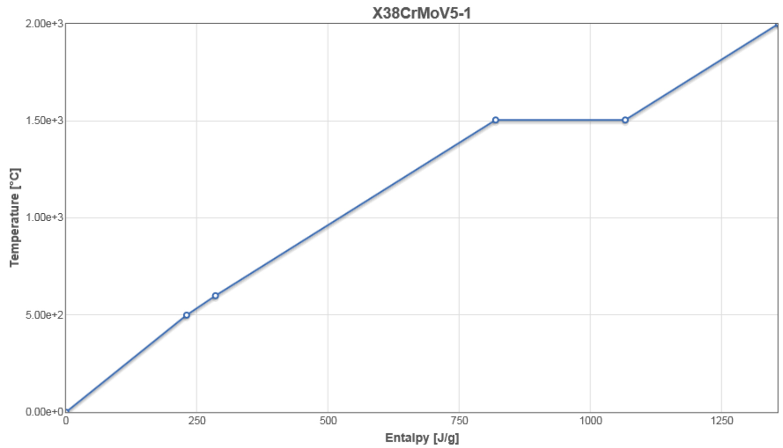
Material properties

- **Required properties for the thermal calculation**
  - Enthalpy-Temperature function - T(H) – (built using specific heat Cp and latent heat L)
  - Thermal conductivity – k(H)
  - Emissivity – ε(H)
  - Density – ρ
  - Absorption a(H)

Fig. 3.59 Measurement of surface tension depending on the temperature of the three alloys investigated



- **Required properties for the CFD calculation**
  - Density - ρ
  - Viscosity - μ(T)
  - Surface tension – σ(T)



*http://www.lucefin.com/wp-content/files_mf/1.2367x38crmov53inglese.pdf

Integrative Production Technology for High-Wage Countries
Christian Brecher
Springer Science & Business Media, 19 déc. 2011 - 1096 pages
(page 156)

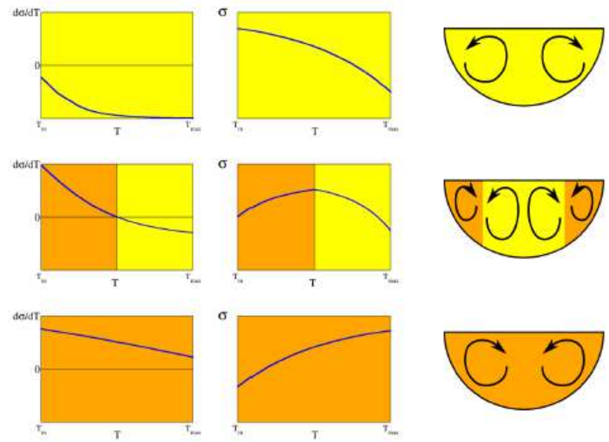
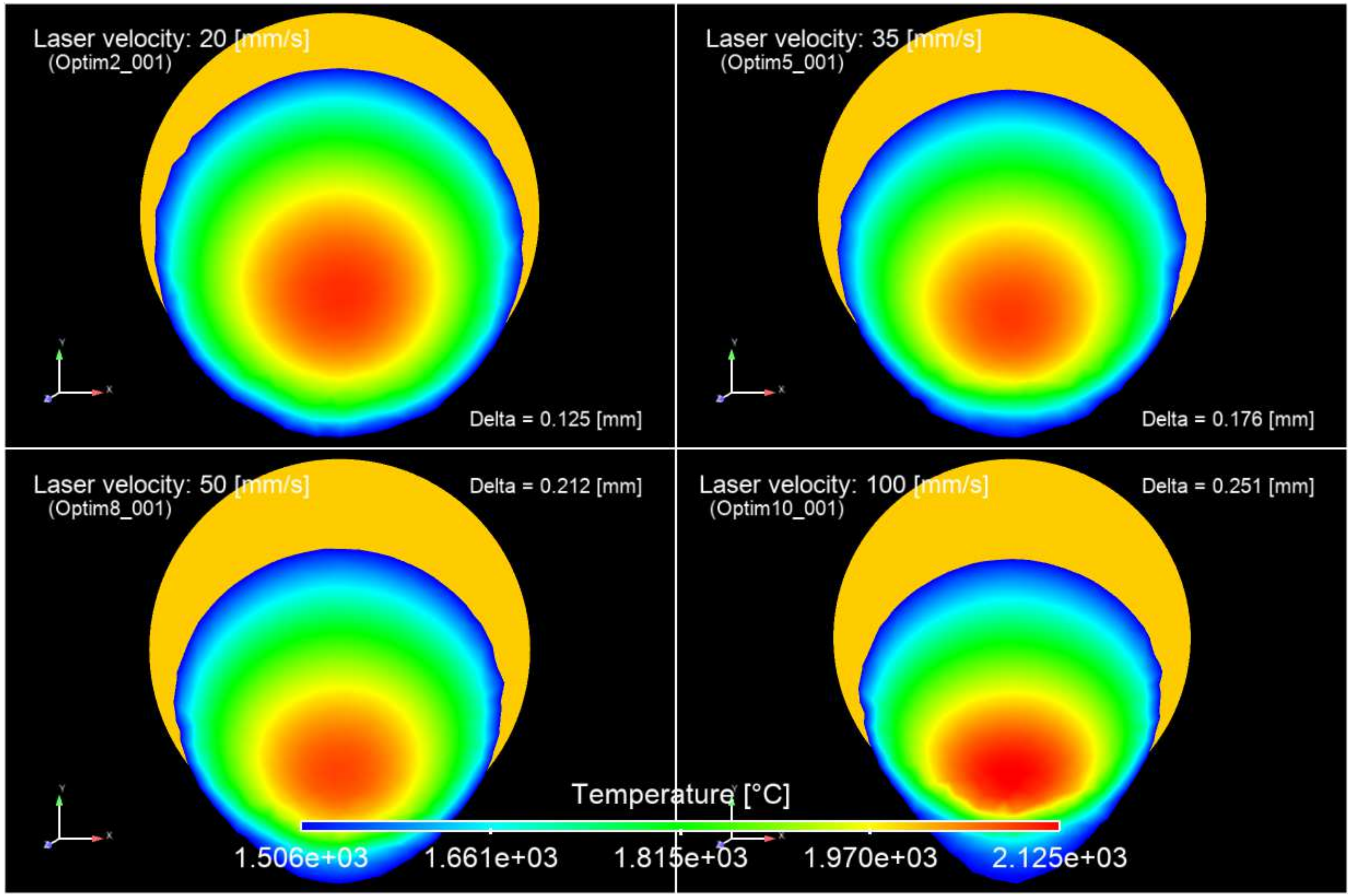


Figure 4.6. Illustration of the relation between the temperature gradient of surface tension between the melting temperature T_m and the maximum weld temperature T_{max}, and the Marangoni flow directions.

Simulation results and comparisons with experimental results

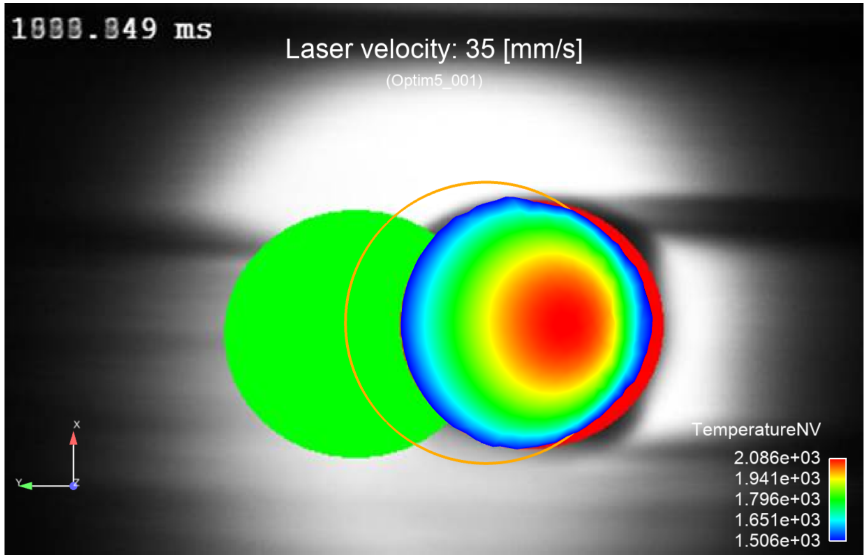
Where is the laser spot with respect to the melt pool?

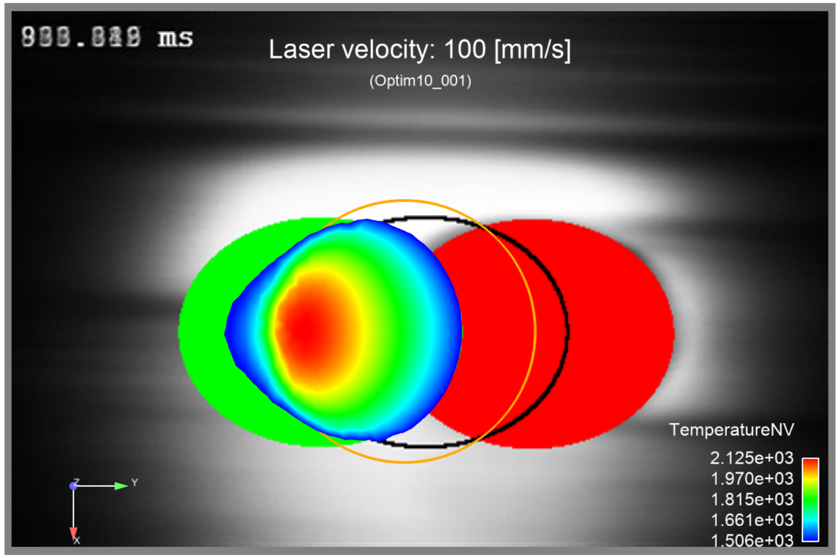
- **Simulation results (*polishing3d*)**

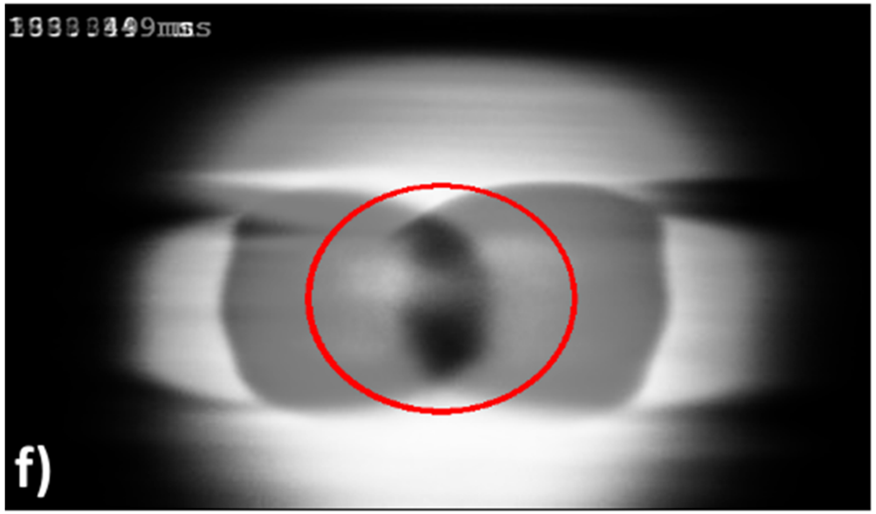


Where is the laser spot with respect to the melt pool?

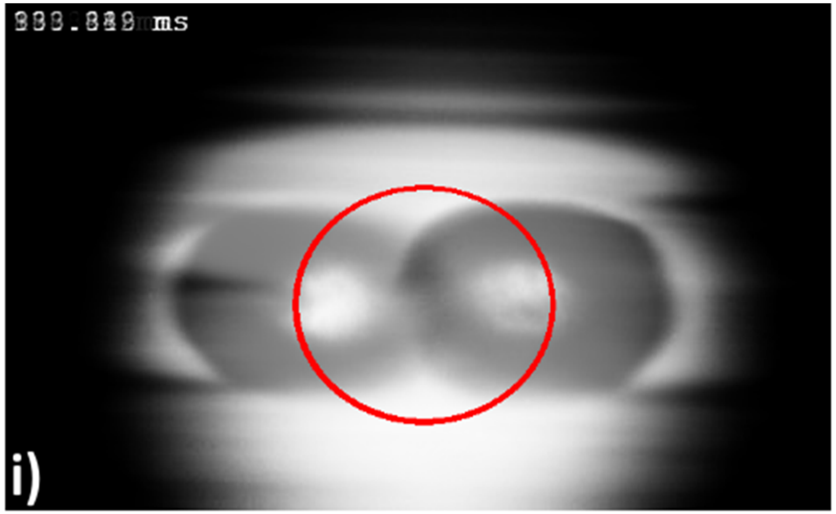
- **Comparison between experimental (EMPA – Dr. Bastian Meylan) and simulation**







The melt pools become more elongated when the velocity increases.



The melt pools are trailing more when the velocity increases

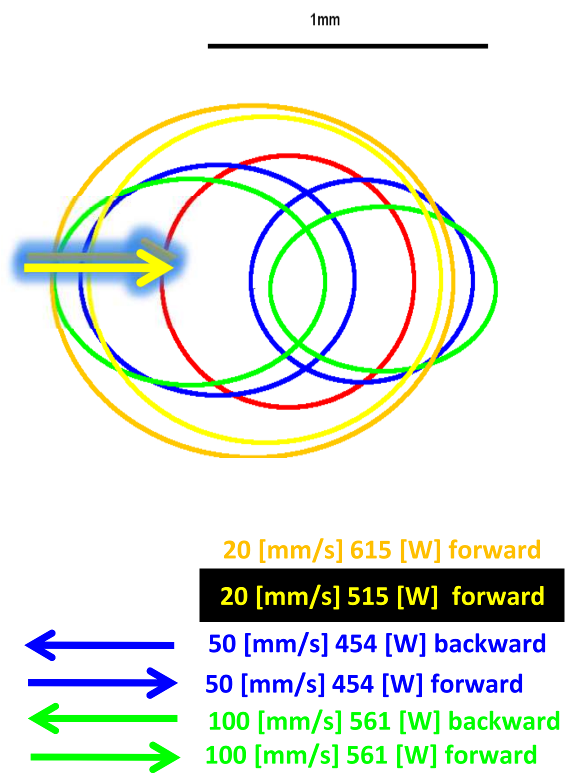
Where is the laser spot with respect to the melt pool?

- **Comparison between experimental and simulation results**

	X width µm	Y width µm	X center µm	Y center µm	center shift µm
Experimental results:					
20 [mm/s] - 515 [W] forward	1257	1166	789	1035	-82
20 [mm/s] - 615 [W] backward	1433	1259	746	1042	-126
50 [mm/s] - 454 [W] forward	977	824	620	1037	-251
50 [mm/s] - 454 [W] backward	795	724	1135	1040	263
100 [mm/s] - 561 [W] forward	965	738	520	1043	-351
100 [mm/s] - 561 [W] backward	807	588	1211	1068	339
Simulation results:					
20 [mm/s] - 359[W] Optim2_001	837	387	-	-	-90
20 [mm/s] - 615 [W] OptimFinal_007	1240	1039	-	-	-177
20 [mm/s] - 615 [W] OptimFinal_008*	1135	979	-	-	-131
35 [mm/s] - 401 [W] Optim5_001	807	808	-	-	-130
50 [mm/s] - 438 [W] Optim8_001	794	779	-	-	-159
50 [mm/s] - 454 [W] OptimFinal_001	826	794	-	-	-159
100 [mm/s] - 561 [W] OptimFinal_006	819	762	-	-	-212

* Changing the absorption curve

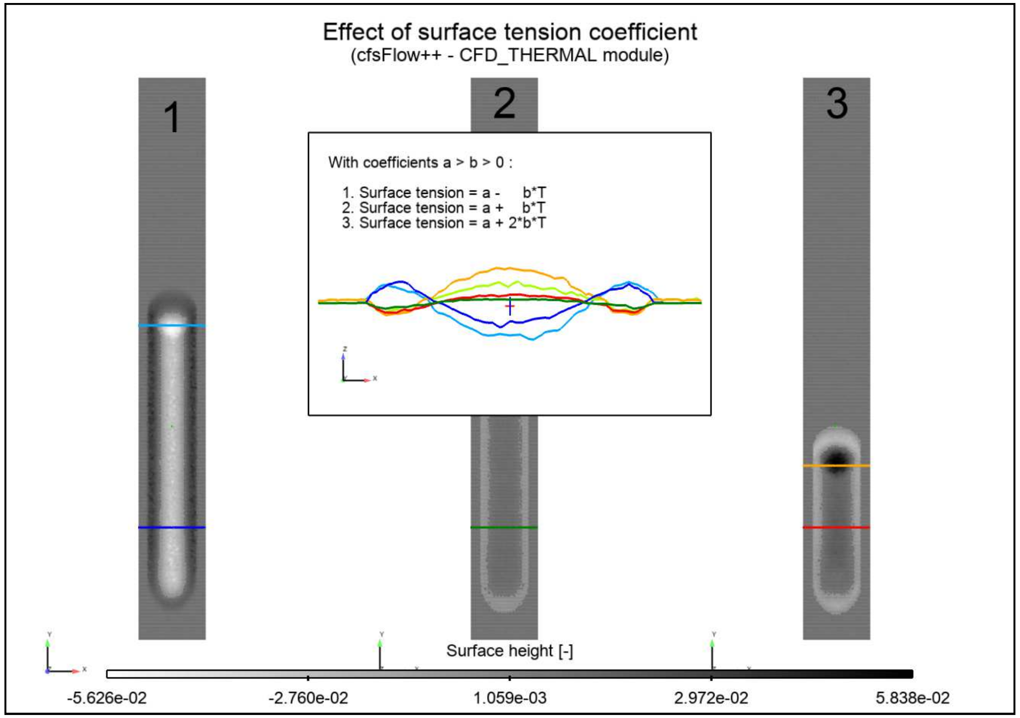
Experimental measurements:

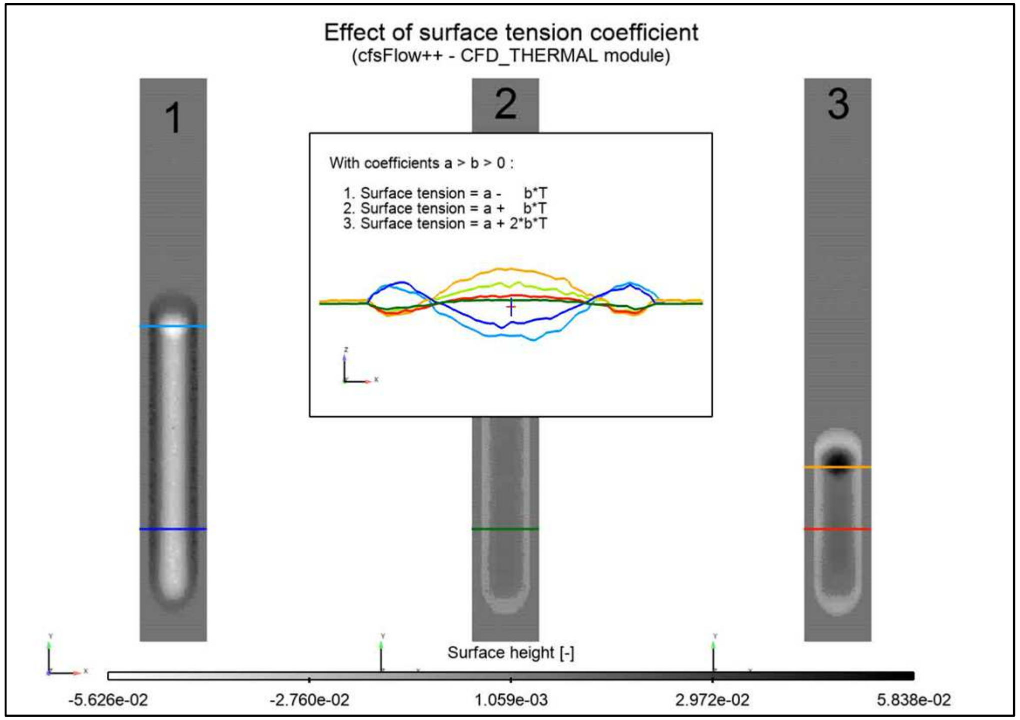


- **Conclusions:**
  - The magnitude of the size of the melt pool and of the center shift are correct
  - For experimental results, the center shift seems greater although the melt pool is also greater
  - The topology of the melt pools are quite different from a top view. For experimental results, the melt pool looks like an ellipse, which tends to look more like a circle when the laser velocity decreases. For simulation results, the melt pool looks like a circle with a "tail" opposite to the laser direction.

Influence of the surface tension coefficient values

- **Simulation results (cfsFlow)**

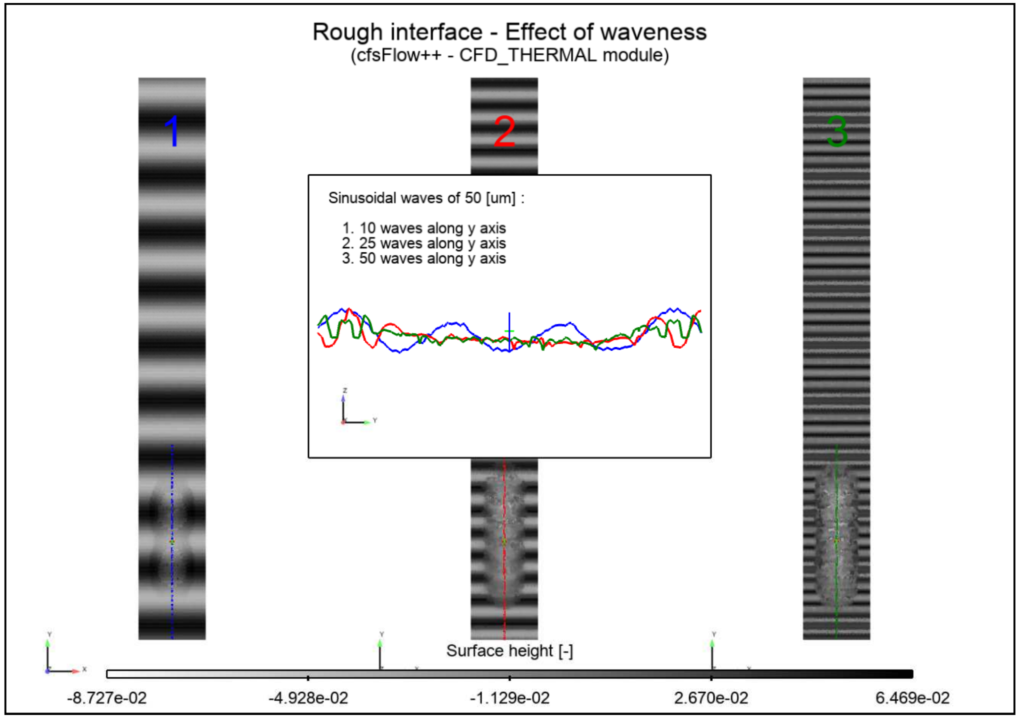


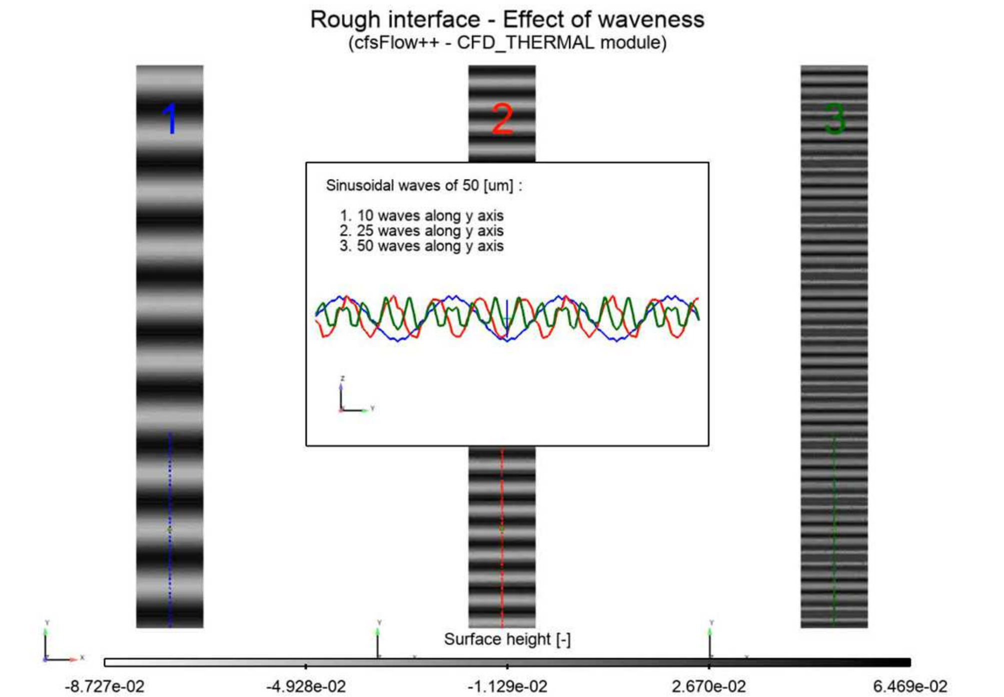


- **Conclusions :**
  - The simulation can reproduce the influence of the surface tension term for the resulting treatment of a flat surface.

Influence of the surface's waviness?

- **Simulation results (cfsFlow)**





- **Conclusions :**
  - The simulation can reproduce the surface's waviness effect observed in the experiments.
  - The weak coupling between thermal and CFD problems limits the quality of results!

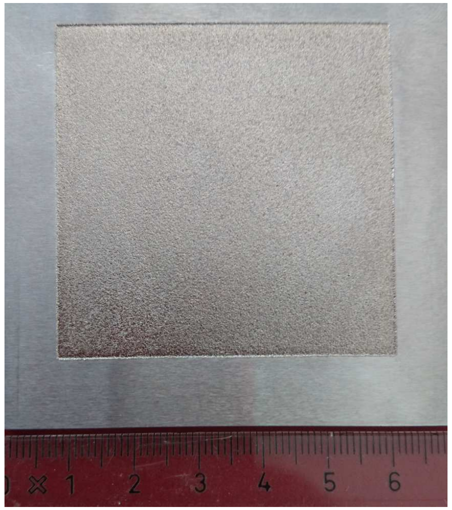
Conclusions about simulations for this process

- **Benefits of the project**
  - It is now possible to simulate the laser melting treatment process
  - The obtained results show good agreement with EMPA experimental results from a qualitative point of view
  - From an industrial point of view, the software now allows to test sensibility to parameter variations (laser power, laser velocity, laser diameter, scanning strategy, material composition, geometrical aspects (2D-3D), etc.).
- **Qualitative to quantitative results**
  - Almost all simulation results are qualitative and in good agreement with experimental results. To obtain quantitative information some parameters must still be calibrated and efforts are necessary to improve local precision of simulations
  - Improvements are necessary to reduce the consuming simulation time
  - The importance of the resulting microstructure of the material after the treatment requires the addition of a specific module to resolve such a problem. This module must be coupled with thermal and CFD problems
  - Experimental results like measures about the velocity field and thermal gradient would also be beneficial
- **Next steps:** **Strong coupling (free surface) – structure phase transition material module**

Acknowledgements

- **Unitechnologies (M. Ivan Calderon, M. Prélaz Jean-Claude) for this project and for their trust during its accomplishment**
- **Innosuisse (KTI-CTI) for its financial support**
- **EMPA group (Dr. Wasmer Kilian, Dr. Bastian Meylan, Prof. Patrik Hoffman) for this successful collaboration**
- **Professors Roland Logé and Marco Picasso for their scientific support and for hiring me**
- **Professor Eric Boillat, for his suggestions, for his help and for his joint work during the project**

Polishing of tool steel with EDM surface (EMPA – Unitechnologies)



Initial roughness : 4.1 µm

Final roughness : 0.6 µm

Why not using an industrial software in this project?

- **Scientific reasons**
- **Technical reasons**
- **Pricing reasons**