Finite element prediction of laser-material interaction using COMSOL Multiphysics ®

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Content

1. Working with SIMTEC
2. Modelling for innovative application
3. How to model laser surface texturing?
4. Lesson learnt and future work

Working with SIMTEC

Industry Challenges

- R&D sections: experts in their field
  → Expertise in numerical modelling?
- Lack of time
- FE modelling performed by a small group of people

SIMTEC's Solutions

- Numerical modelling project
  → SIMTEC's member as your colleague
  → Help improve your modelling knowledge!
  → Cost-effective outsourcing

Our team & Our clients

COMSOL
Certified Consultant

Numerical Modelling Consultants

6 Members all EngD + PhD

- Extensive research background
- Complex problems
- various fields of expertise

Successful Track Record:

- Big international compagnies
- Government laboratories

Involved in Research Consortia

- EU funded projects (REEcover / SHARK)
- PhD projects supervision.

EUROPEAN COMMISSION
SEVENTH FRAMEWORK PROGRAMME
REEcover
SHARK
INDUSTRIALISING LASER FUNCTIONAL TEXTURING

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Content

1. Working with SIMTEC
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3. How to model laser surface texturing?
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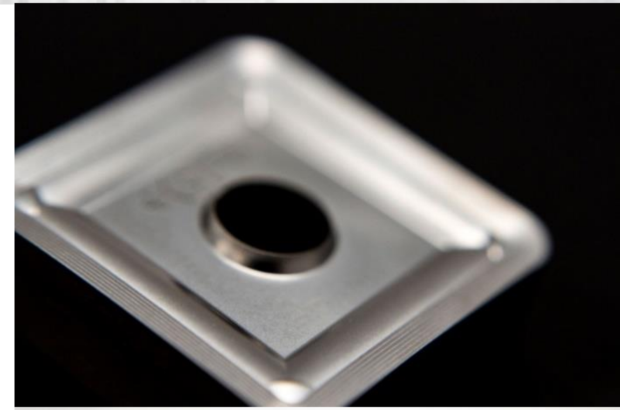
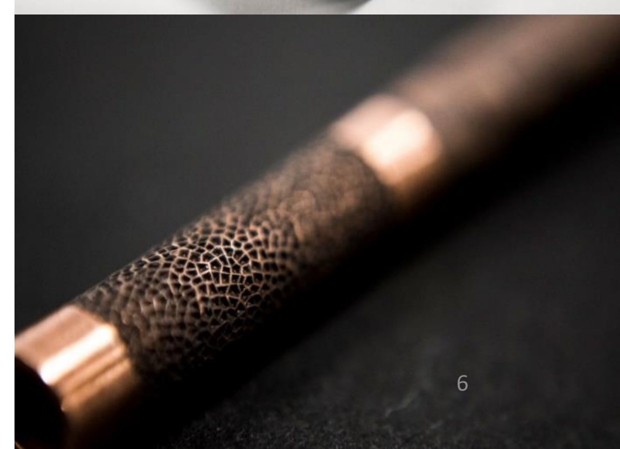
Context

- Surface functionality
  - Friction coefficient
  - Anti-bacterial properties
  - Anti-icing properties
- Texturing processes
  - Surface coating
  - Laser surface texturing
- SHARK project
  - Bring laser surface texturing to industry
  - Advise on the laser parameters selection



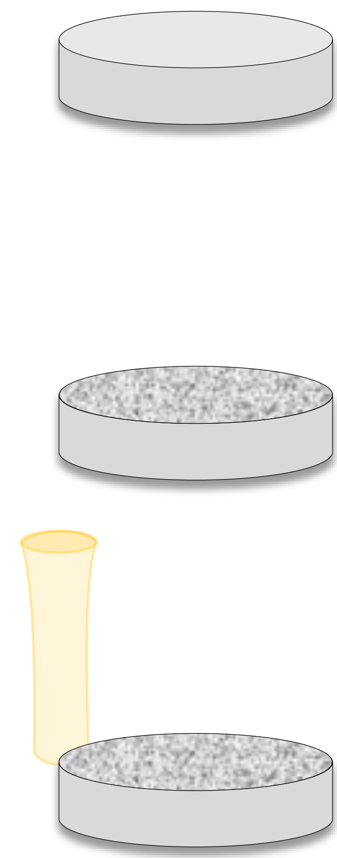


Context

- User
  - Specimen, shape, material
  - Desired surface function
  - Machine: - « laser parameters? »
  (frequency, pulse duration, average power …)

- Surface function → Topography

- Topography → Laser parameters



Direct problem
→ Topography prediction from a set of laser parameters

Content

Modelling laser texturing

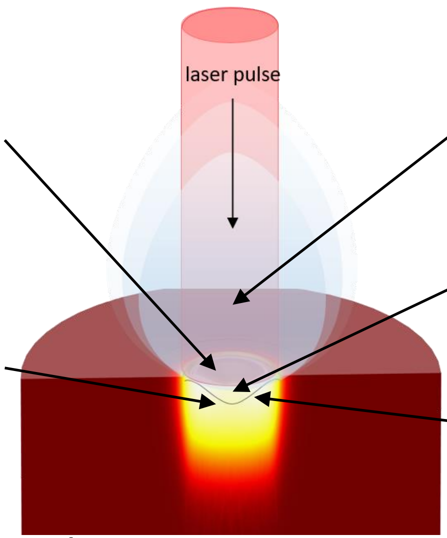
- Physical phenomena and assumptions
  - Topography prediction

  →Need to understand complex physical mechanisms

  - Multiphysics and multiscale problem
    - M. Dal and R. Fabbro, *Optics&LaserTechnology,* no. 78, pp. 2-14, 2016.
    - A. Otto and M. Schmidt, *Physics Procedia 5,* pp. 35-46, 2010.

Absorption
- Fresnel absorption
- multiple reflections
- vapour and plasma absorption
- temperature dependent optical properties

Heat tranfers
- convective and conductive heat flux
- melting and evaporation enthalpy



Vapour dynamics
- pressure waves
- Bernoulli effect

Melt dynamics
- melt expulsion, spilling formation
- Marangoni convection
- temperature dependent material properties

Phase transitions
- melting and solidification
- evaporation and condensation
- vapour pressure on the interface
- mass flux between phases

- One impact → 2D-axisymmetric geometry

Modelling laser texturing

- Electromagnetic problem
  - Laser source description
  - Laser/matter interaction
- Thermal problem
  - Energy equation

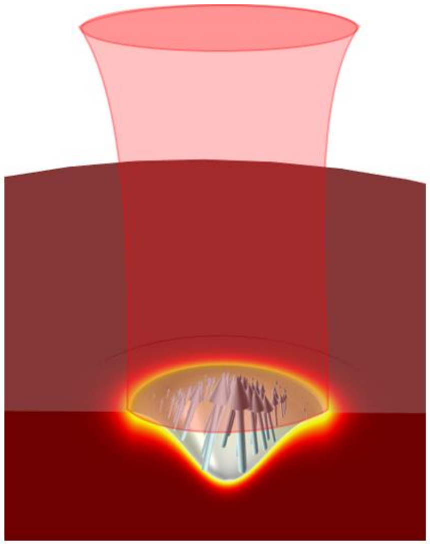
$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \boldsymbol{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q_i$$

  - Phase changes: vaporisation and melting
- Fluid Dynamics (CFD)
  - Mass and momentum equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = \nabla \cdot \left[-p\bar{\bar{I}} + \eta(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T)\right] + \boldsymbol{F_g}$$

  - Recoil pressure
  - Surface tension and Marangoni effects



Modelling laser texturing

- Energy equation

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = 0$$

- Boundary conditions
  - Thermal heat flux

$$-\boldsymbol{n} \cdot (-k\nabla T) = P_{laser} \cdot \frac{A_0}{\pi \left(\frac{w_0}{2}\right)^2}$$

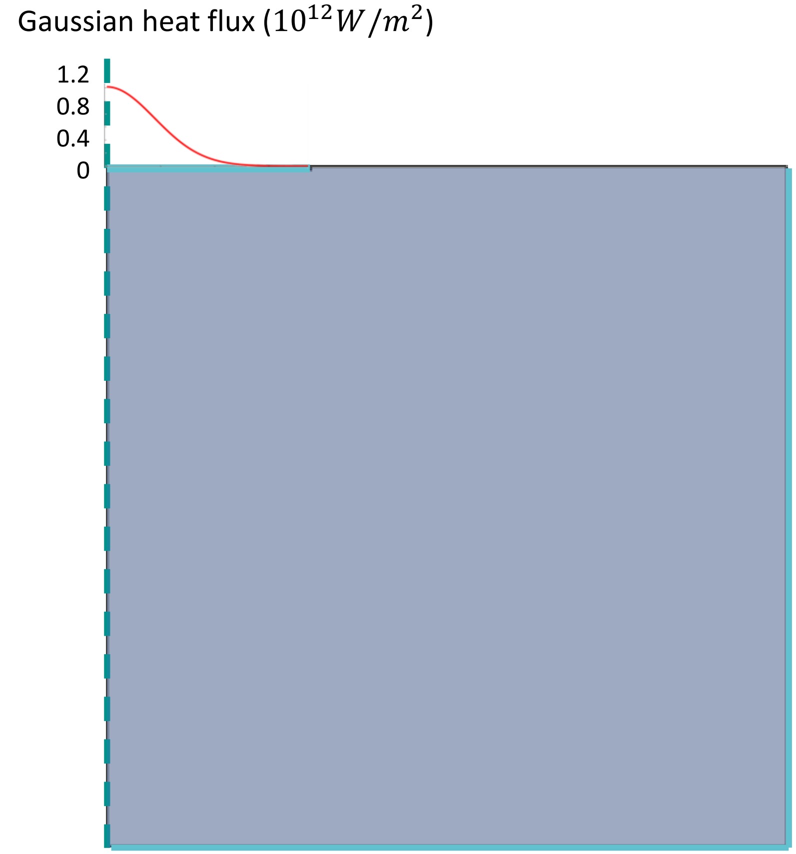
  - Numerical convective heat flux

$$Flux_{vap} = h \cdot (T - T_{vap})$$

  - Thermal insulation

$$-\boldsymbol{n} \cdot (-k\nabla T) = 0$$

  - Axial symmetry



Modelling laser texturing

- Phase change modelling
  - Vaporised matter velocity

$$v_{vap} = \frac{Flux_{vap}}{\rho L_v}$$

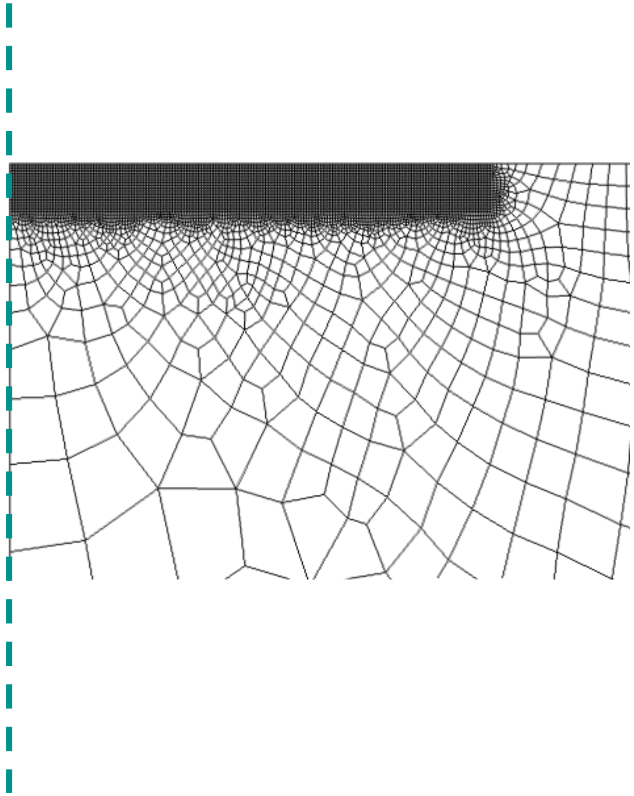
where L_v is the latent heat of vaporization

  - Mesh deformation

$$\boldsymbol{v_{mesh}} \cdot \boldsymbol{n} = v_{vap}$$

where $\boldsymbol{n}$ is the surface normal vector

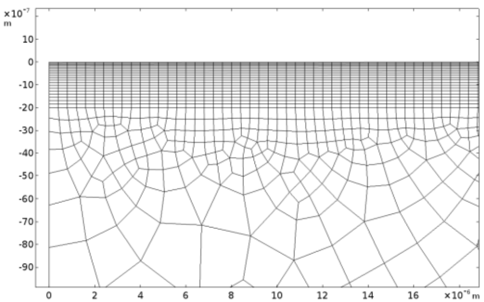
  - Mass balance not at equilibrium



Numerical aspects and validation

- Highly non-linear and strongly coupled problem solved with
  - Fine mesh
  - Accurate time-discretization
  - Adapted solver

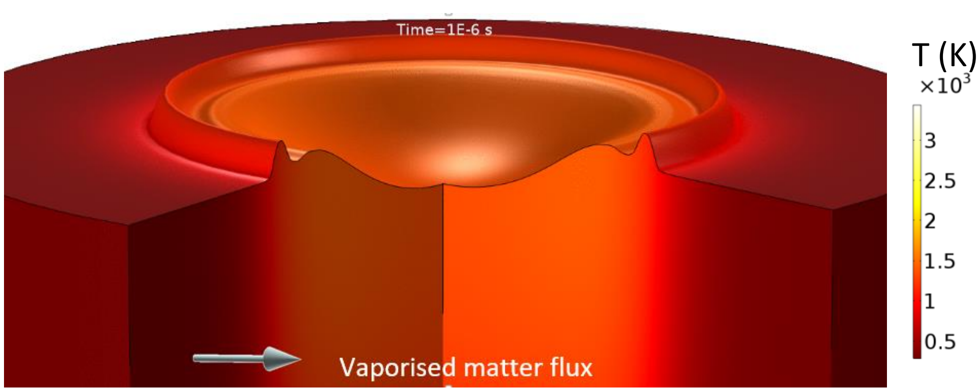
COMSOL



- Numerical validation
  (Mass and energy balances)

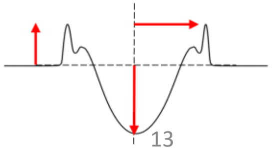
- Results

Inputs
- Laser parameters
- Material properties



Deformation x 20

Outcome
- Topography (width, depth, peak)



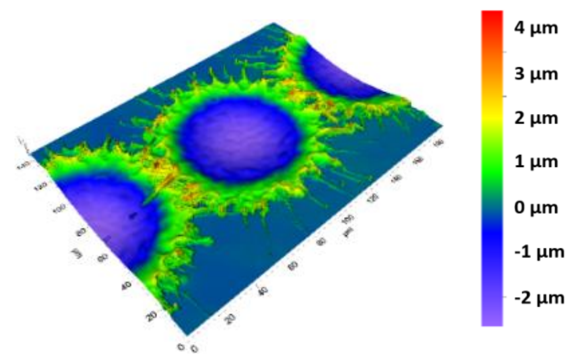
Experimental results

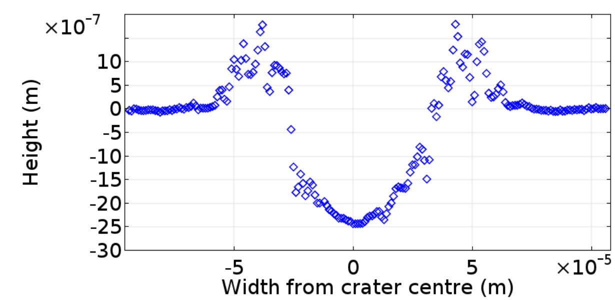
- MTC
  (The Manufacturing Technology Centre)

- Laser parameters
  - Spot ablation (average power, pulse energy)

- Optical metrology equipment
  - 2D/3D profiles

Parameters	Spot ablation
Pulse duration (ns)	200, 100, 50
Beam speed (mm/s)	3000
Frequency (kHz)	30
Power (W)	3, 9, 15, 21, 30

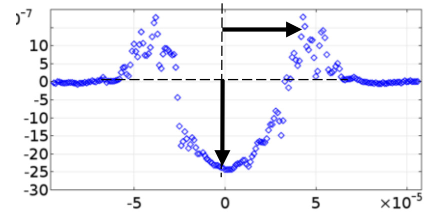


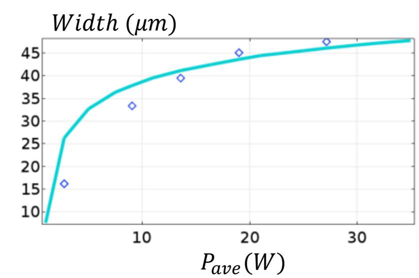


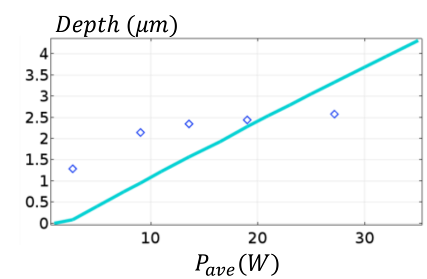
Comparison of FE predicted and experimental results

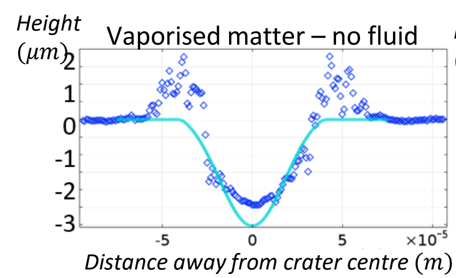
- "Peak-to-peak" distance evolution with power
  - Width evolution tendency satisfactory
- Depth evolution with power
  - Improvement required

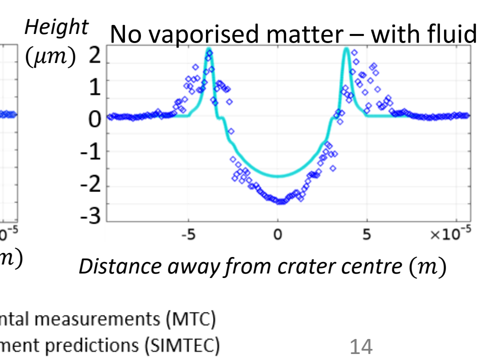
  (Recoil pressure law, absorptivity, material properties, vapour interaction influence …)
- Peak creation
  - Fluid modelling required





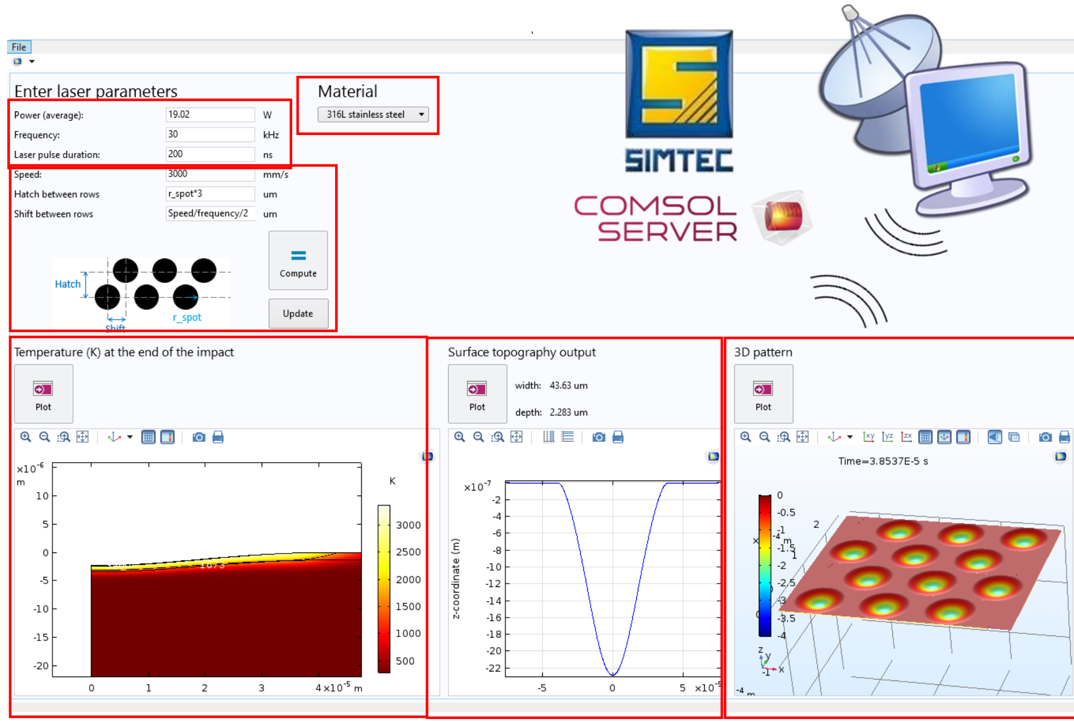






Application built from the model

- Inputs
  - Laser parameters
  - Laser path
  - Material (database)



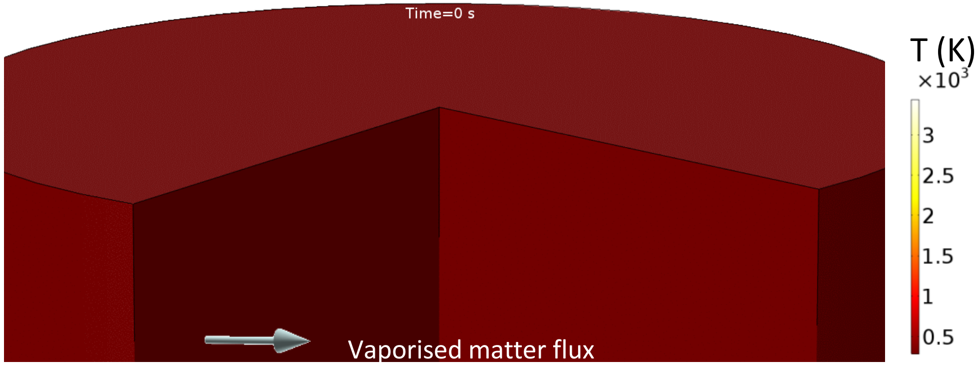
- Outcome
  - Temperature field
  - 2D profile of a single impact (width, depth)
  - Plot 3D pattern

- Application ran on SIMTEC's servers

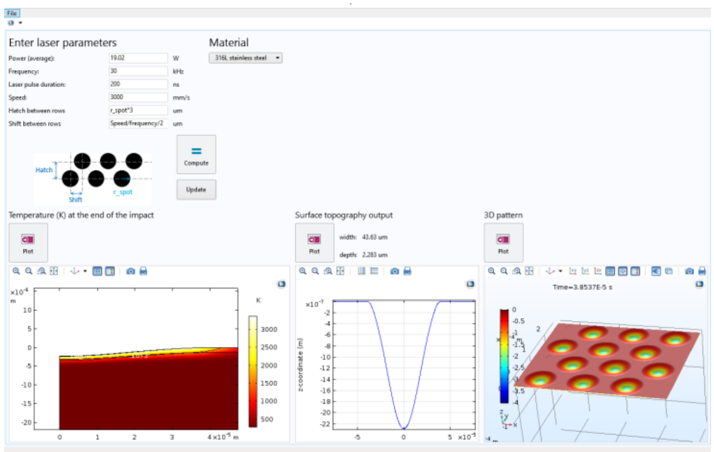
Content

Summary

- Numerical modelling approach of laser material interaction
- Comparison of prediction against experimental measurements
- Topography prediction application to be ran remotely on SIMTEC's servers



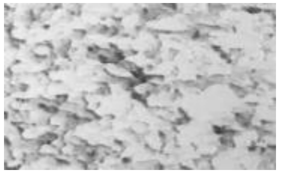
Deformation x 20



Future Work

- More materials for experimental comparison

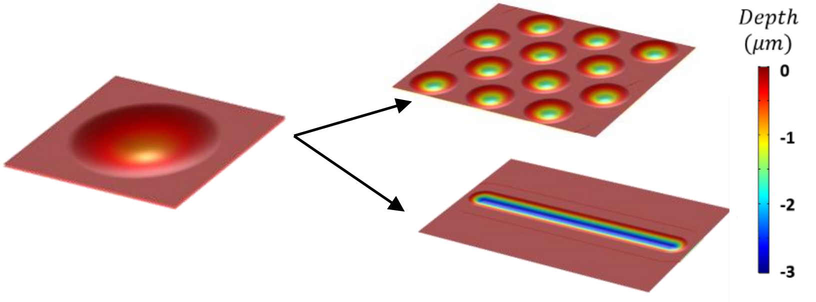
- Initial surface influence on final topography
  - Surface roughness



Sa = 0.25 µm

Sa < 0.15 µm

- Beyond a single impact
  - Multipass, DLIP, overlap, grove



Thank you !

SIMTEC

SHARK
INDUSTRIALISING LASER FUNCTIONAL TEXTURING

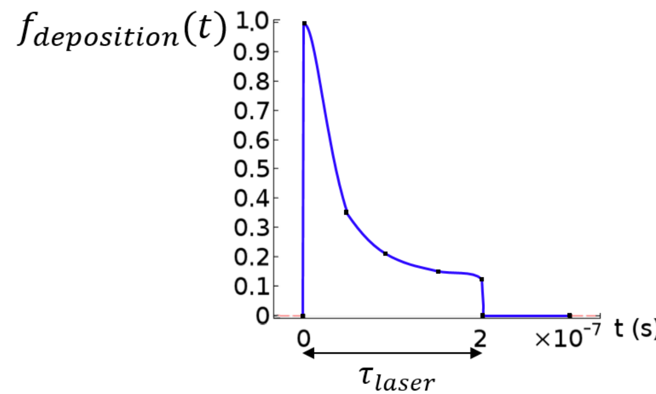
This project has received funding from the European Union's Horizon 2020 Framework Programme for research and innovation under grant agreement No 768701.

Electromagnetic problem

- Laser source description
  - Thermal heat flux

$$-\boldsymbol{n} \cdot (-k\nabla T) = P_{laser} \cdot \frac{A_0}{\pi \left(\frac{w_0}{2}\right)^2}$$

  - Time-dependent
  - Interpolation from experimental data



- Laser-matter interaction
  - Absorptivity coefficient

Thermal Modelling

- Energy equation

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) = 0$$

- Boundary conditions
  - Thermal heat flux

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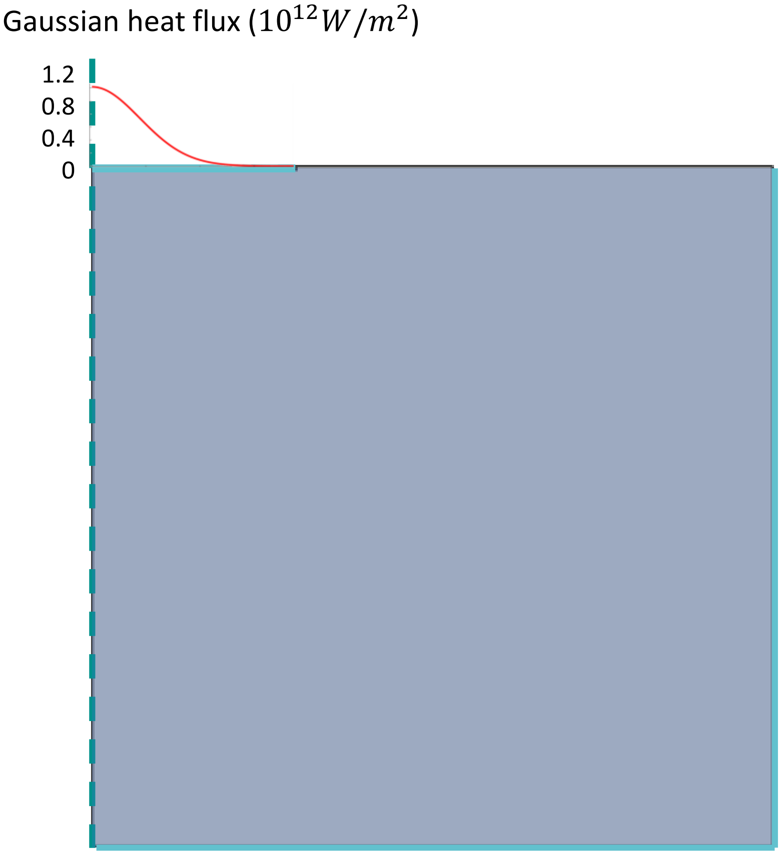

Thermal Modelling

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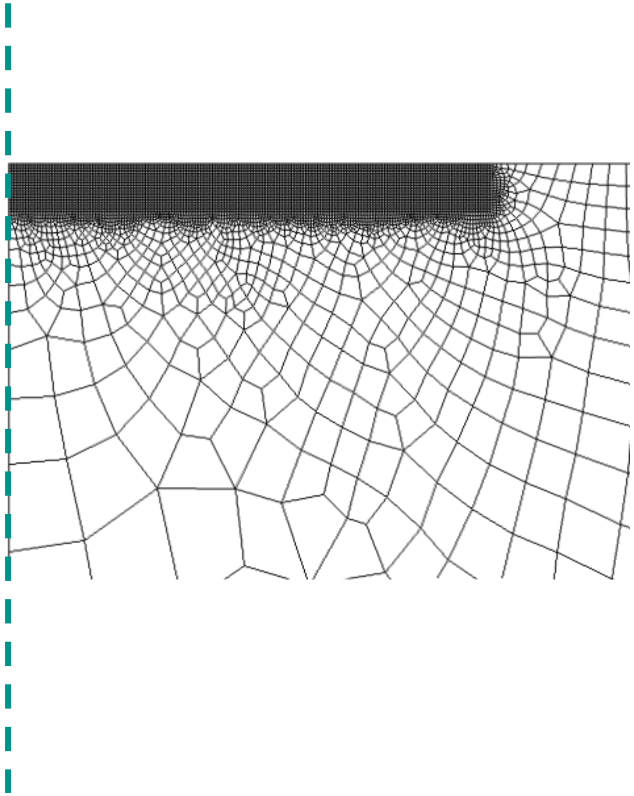
  - Mass balance not at equilibrium

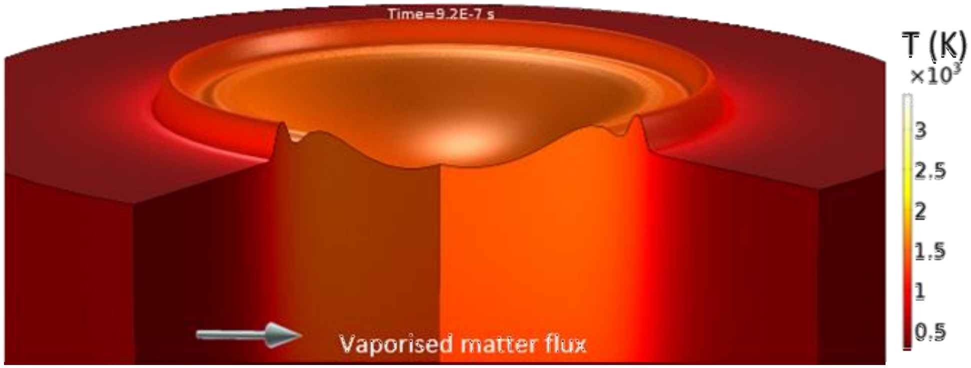


Laser material interaction modelling

- Fluid modelling
  - Navier-Stokes equations

$$\begin{cases} \nabla \cdot \rho \boldsymbol{u} = \boldsymbol{0} \\ \rho(\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u}) = \boldsymbol{\nabla} \cdot \left[-p\bar{\bar{I}} + \eta(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T) - \frac{2}{3}\eta(\nabla \cdot \boldsymbol{u})\bar{\bar{I}} \right] + \rho \boldsymbol{g} \end{cases}$$

  - Recoil pressure
  - Surface tension and Marangoni effects



Deformation x 20