POLITECNICO MILANO 1863

mecc
DIPARTIMENTO DI ECCELLENZA
MIUR 2018-2022

Production 4.0 – Teaching Lab at DMecc

Advanced Manufacturing Processes

Lab 1 – Revision 1

Scheduling of laboratory activites

Lab 0 – Guidelines -- Today

- Introduction to lab Production 4.0
- Presentation of lab set up
- Presentation of case study

Lab 1 – Revision 1 -- 27^{th} September

- Moving heat source theory
- Implementation of thermal model in MATLAB
- Experimental data provided for efficiency calibration

28^{th} September -------- Deadline for group registration

Lab 2 – Revision 2 -- 25^{th} October

- Revision of MATLAB code
- Definition of process parameters
- Gcode generation for testing optimised process parameters

Lab 3 – Revision 3 -- 3^{rd} December

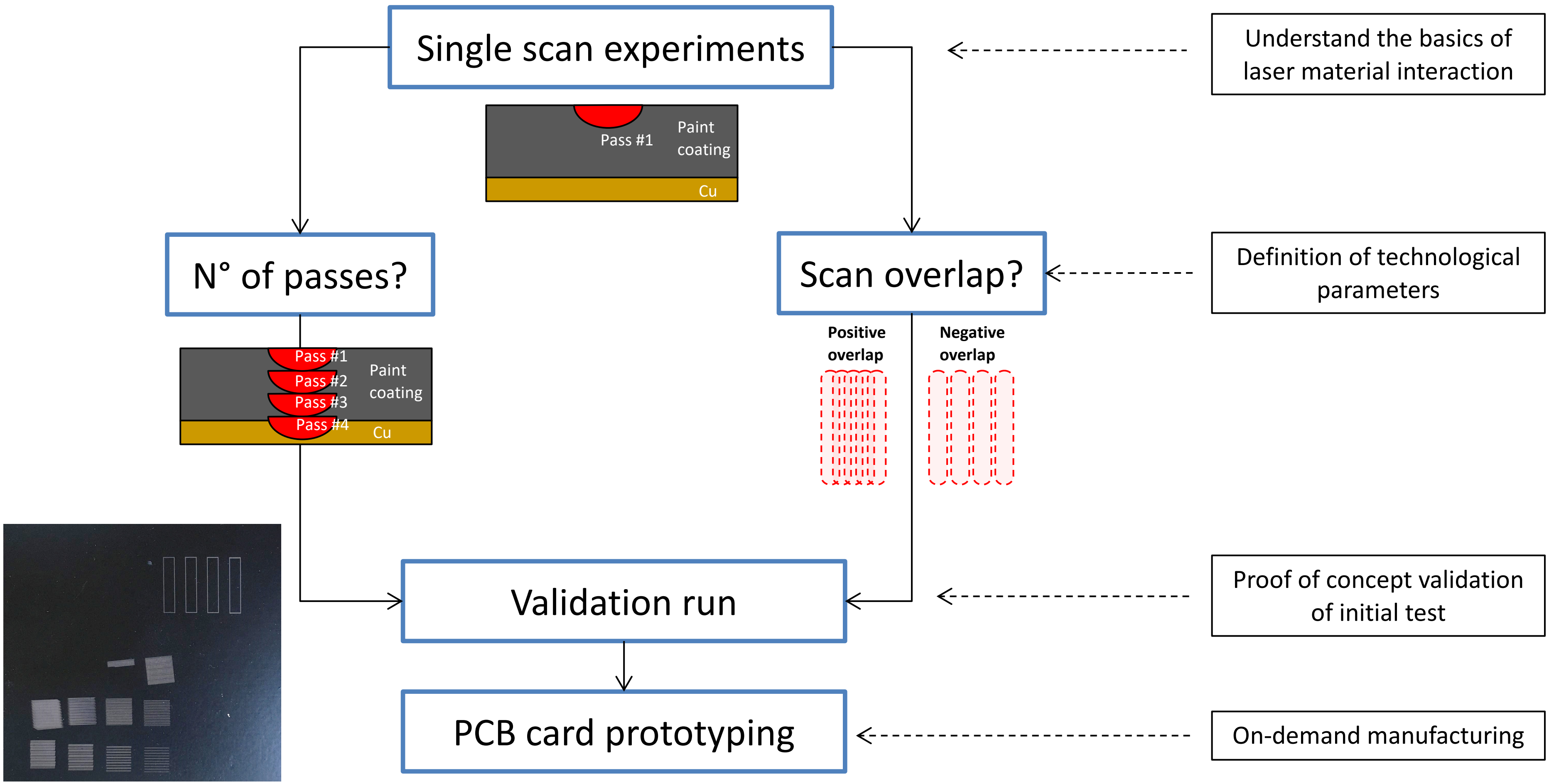
- Revision of manufactured workpieces
- Critical project considerations and comments

31^{st} December -------- Forms hand-in for lab work evaluation

On-demand manufacturing of custom PCB boards

Aim of the project:

Design the manufacturing process for custom PCB board production

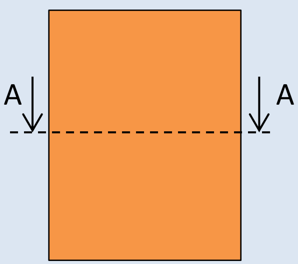


On-demand manufacturing of custom PCB boards

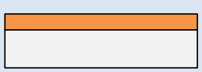
PCB prototyping process

1

25 µm Cu coating over FR-4 fiber glass

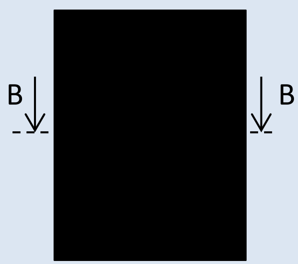


SECTION A-A

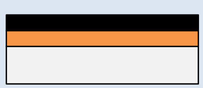


2

Paint coating over Cu coating

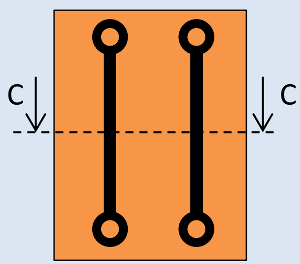


SECTION B-B

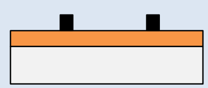


3

Selective laser stripping

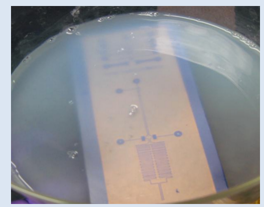


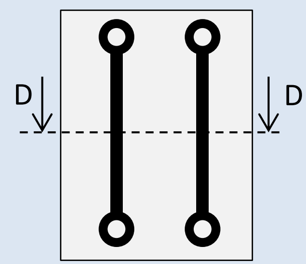
SECTION C-C



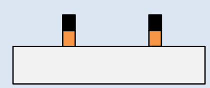
4

Selective chemical etching



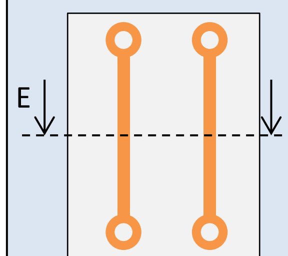


SECTION D-D

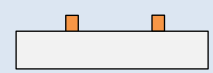


5

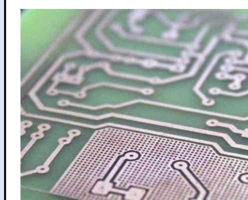
Chemical washing



SECTION E-E



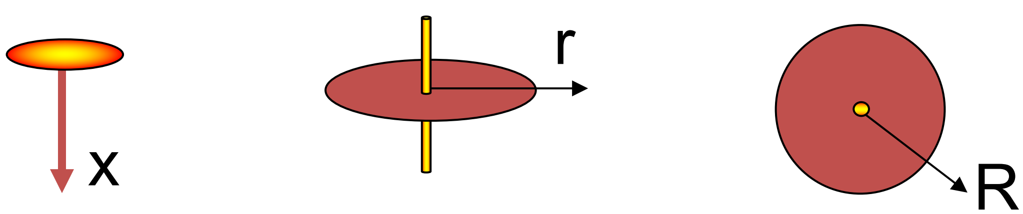
Final product: PCB card



Drawings not to scale

Common analytical solutions of thermal models

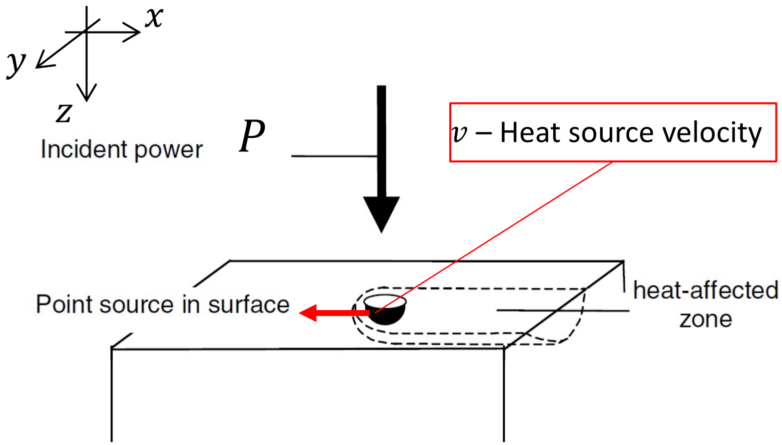
Beam movement		Source type – Temperature gradient		
		Planar source Only in thickness x	Line source Normal to the beam plane – Material surface x and y	Point source Every direction x,y and, z
	Motionless beam	Time dependant T(x,t)	Time dependant T(x,y,t)	Time dependant T(x,y,z,t)
	Moving beam	Quasi-stationary T(x,v)	Quasi-stationary T(x,y)	Quasi-stationary T(x,y,z)



We will develop simple and opportunistic models for estimating process behaviour

Thermal model – Problem formulation

Point heat source model



Dowden, The mathematics of thermal modeling

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$ Heat equation

$$\boxed{T(x, y, z, t) = ?}$$

Solution workflow

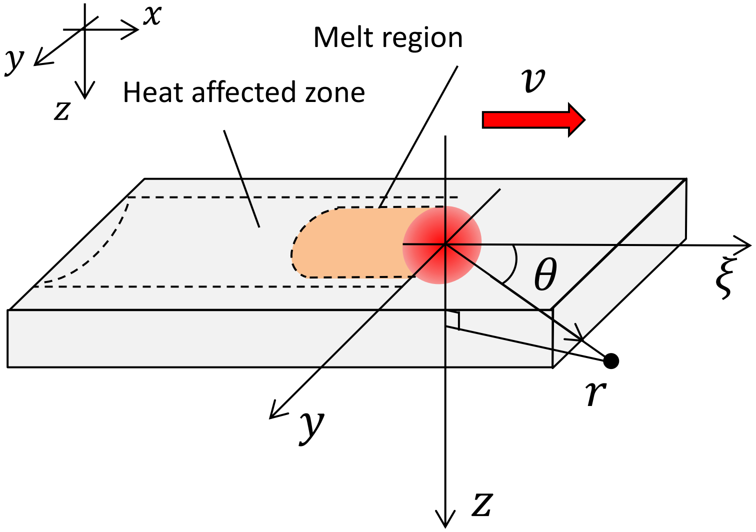
- Define process conditions
- Determine hypothesis
- Impose boundary conditions
- Solve mathematical problem

Main PARAMETERS

κ – Thermal conductivity (W/mK)
α – Thermal diffusivity (m^2/s)
v – Heat source velocity (m/s)
P – Incident power (W)

Thermal model – Hypothesis & BCs

Point heat source model - Hypothesis

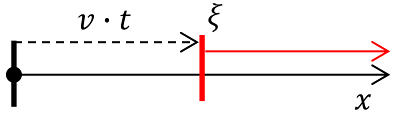


Relative coordinates

Observer moving with heat source at speed v

→Stationary problem

$\xi = x - v \cdot t$



No convection or radiation heat transfer

Steady state conditions

Constant ambient temperature

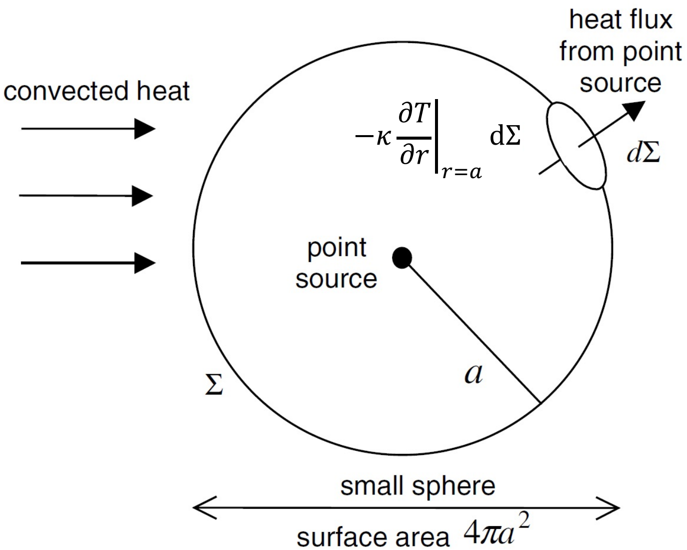
Homogeneous & isotropic material

Constant thermal properties

Point source boundary conditions

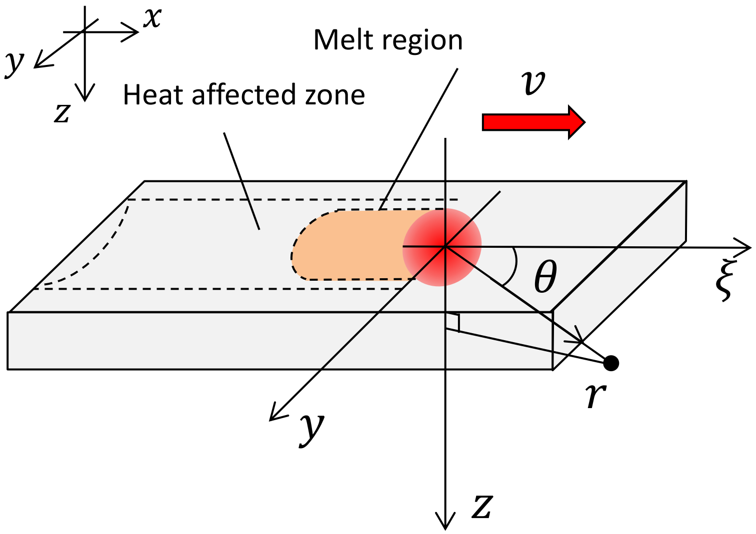
→ Assume point source is at the interior of material

→ All power input flows through an infinitesimally small sphere of radius *a*



Thermal model – Solution

Point heat source model



$$T(x, y, z, t) = ?$$

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$ Heat equation

$$T(\xi, y, z) = T_0 + \eta \cdot \frac{P}{2\pi\kappa r} e^{-\frac{v}{2\alpha}(\xi + r)}$$

$$T(\xi, y, z) = T_0 + \eta \cdot \text{f (Process parameters, material properties)}$$

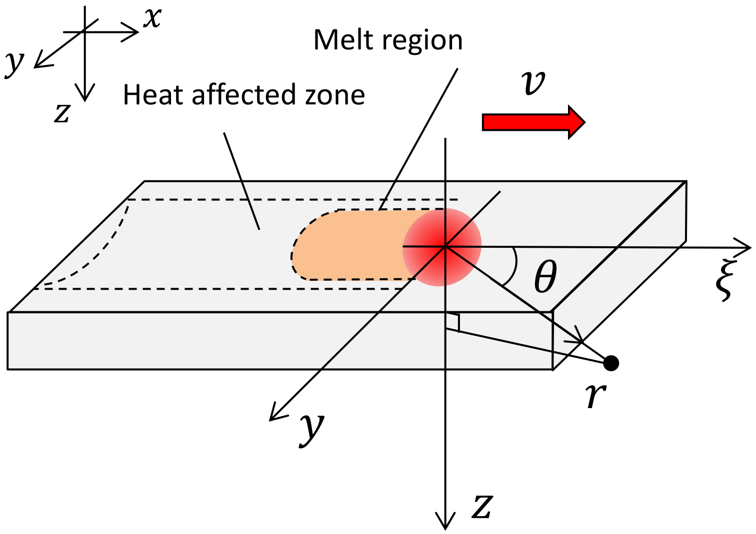
$$\alpha = \frac{\kappa}{\rho c_p}$$

$$r = \sqrt{\xi^2 + y^2 + z^2}$$

η – Process efficiency
κ – Thermal conductivity (W/mK)
α – Thermal diffusivity (m^2/s)
c_p – Heat capacity (J/kgK)
x – Spatial x-coordinate (m)
r – Radius from heat source origin (m)
v – velocity of heat source (m/s)
T_0 – Ambient temperature

Thermal model – Solution

Point heat source model



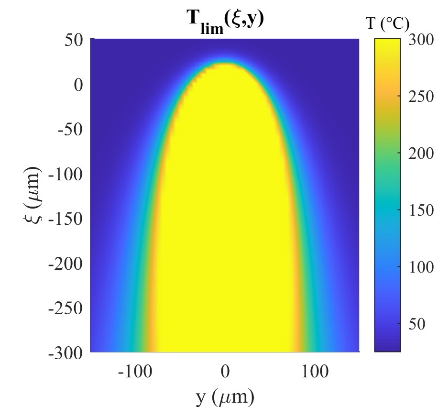
$$T(\xi, y, z) = T_0 + \eta \cdot \frac{P}{2\pi\kappa r} e^{-\frac{v}{2\alpha}(\xi + r)}$$

$$r = \sqrt{\xi^2 + y^2 + z^2}$$

<u>What does the process efficiency coefficient η represent?</u>

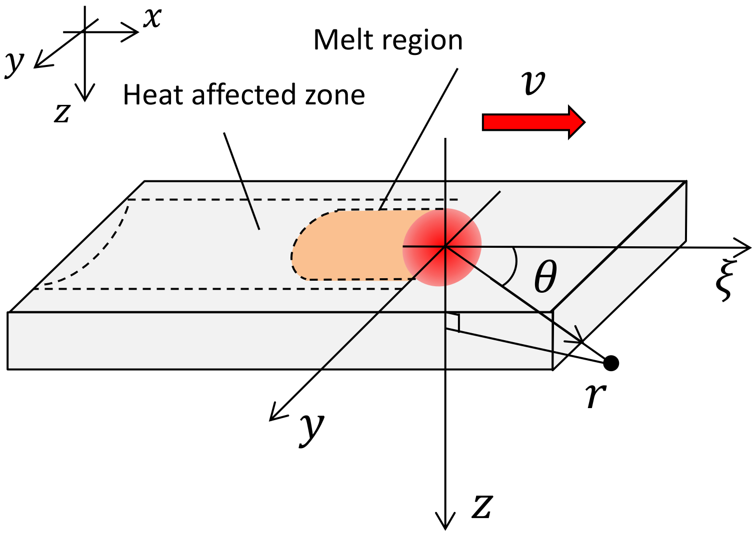
If calibrated allows to take into account modelling inaccuracies:

- Reflection of the incoming light
- Fluid dynamic aspects
- Other means of heat transfer
- Effect of other process parameters



"All models are wrong, but some are useful"
George E.P. Box (famous statistician)

Point heat source model



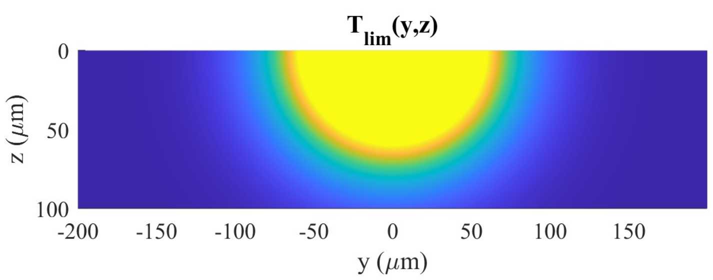
Modified solution

$$\boxed{\begin{gathered} T(\xi, y, z) = T_0 + \eta \cdot \frac{P}{2\pi\kappa r} e^{-\frac{v}{2\alpha}(\xi + r)} \\ r = \sqrt{\xi^2 + y^2 + (c_z \cdot z)^2} \end{gathered}}$$

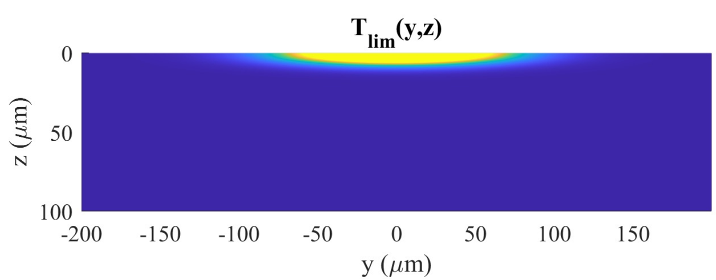
c_z - Geometrical correction factor

Empirical coefficient which indicates different heat diffusion in the workpiece

$c_z = 1$



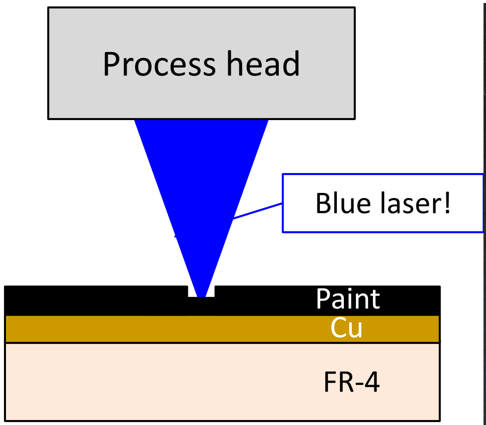
$c_z = 10$

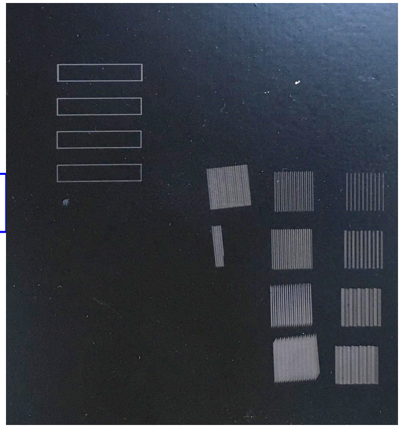


From past experiments, in the case of paint stripping $c_z = 10$

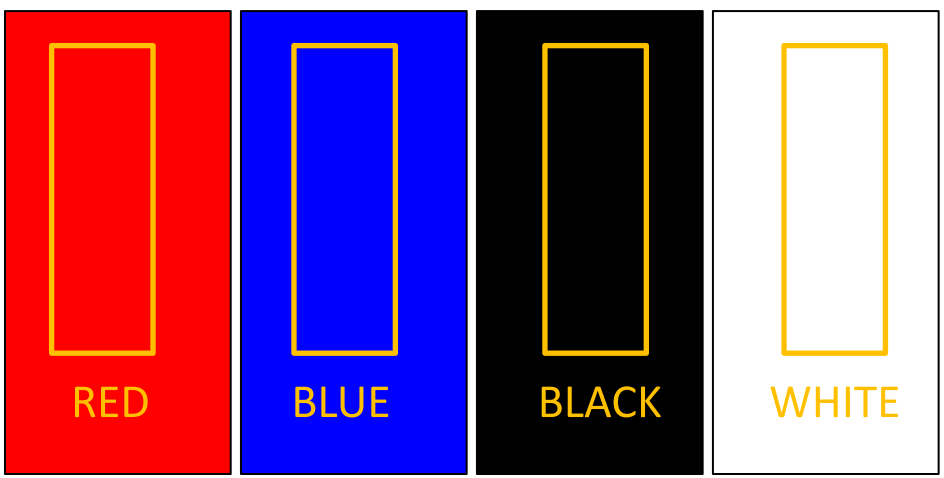
Laboratory 01 - Tasks

Process





Single tracks cannot be drawn on Snapmaker Luban
→ Rectangles with only outer outline



Experimental design:

Fixed factors	
Power, *P* (mW)	1600
Emission wavelength, λ (nm)	445
Focus position, *f* (mm)	0
N° of passes	1
Feed rate, *v* (mm/min)	800
Variable factors	
Paint coating colour	RED – BLUE – BLACK - WHITE

Characterization:

Optical microscope measurement of track width

Aim of the work:

Calculate temperature distribution with $\eta=0.3$

Estimate track width with $\eta=0.3$

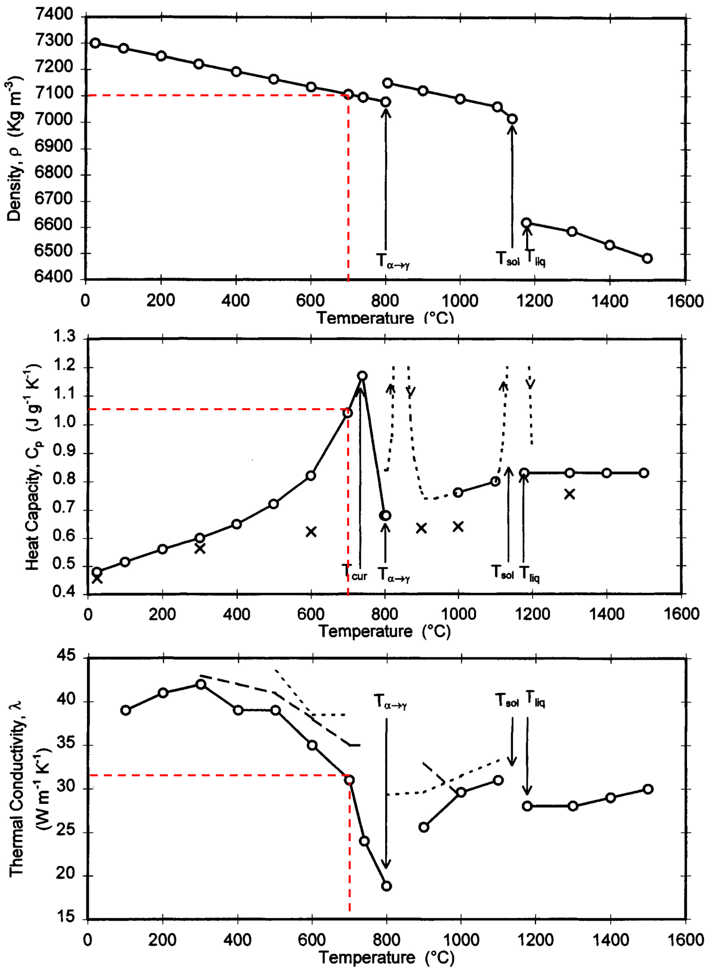
Calibrate efficiency using experimental data

Estimate penetration depth→ n° of passes required?

Define hatch distance to ensure etching of large areas

Thermal model – Example of material properties

Material properties of Ductile iron



Mills, K. C. (2002). *Recommended values of thermophysical properties for selected commercial alloys*. Woodhead Publishing.

Material properties are temperature dependent

We take the material properties at 700 °C

Parameter	Symbol	Value	Units
Density	ρ	7100	kgm^{-3}
Specific heat capacity	c_p	1000	$Jkg^{-1}k^{-1}$
Thermal conductivity	k	32	$Wm^{-1}K^{-1}$
Solidus temperature	$T_{vaporization}$	1140	°C
Liquidus temperature	$T_{liquidus}$	1235	°C
Austenite formation T	$T_{austenitization}$	805	°C

Thermal model – Material properties of paint

Material properties of paint coating

Optik - International Journal for Light and Electron Optics 174 (2018) 46–55

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.com/locate/ijleo

ELSEVIER

<u>Paint coating applied:</u>

Resin-based paint

Reference from literature

Original research article

Removal of paint layer by layer using a 20 kHz 140 ns quasi-continuous wave laser

Zhiyan Zhang[a,b,c], Jingyuan Zhang[b], Yibo Wang[b], Shusen Zhao[b], Xuechun Lin[b,*], Xinyang Li[a,*]

[a] Key Laboratory on Adaptive Optics, Institute of Optics and Electronics, Chinese Academy of Sciences, Sichuan 610209, People's Republic of China
[b] Laboratory of All-Solid-State Light Source, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, People's Republic of China
[c] University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China

Coating thickness: 20 µm

Parameter	**Symbol**	**Value**	**Units**
Density	ρ	1450	kgm^{-3}
Specific heat capacity	c_p	2500	$Jkg^{-1}k^{-1}$
Thermal conductivity	k	0.3	$Wm^{-1}K^{-1}$
Vaporization temperature	T_{vap}	300	°C
Absorption (at λ=1064 nm)	A	0.3	-

Thermal model – Software

Introduction to MATLAB

- Advanced programming software
- Freely available for Polimi students

How to download Matlab:

[Mathworks Matlab – Servizio software di Ateneo (polimi.it)]

For help/suggestions use Matlab documentation

https://it.mathworks.com/help/matlab/

Example of coding structure in Matlab

Physical properties

↓

Process parameters

↓

Simulation domain

Problem statement & variable declaration

↓

Model calculation

Implementation

↓

Save results (optional)

↓

Plot solution

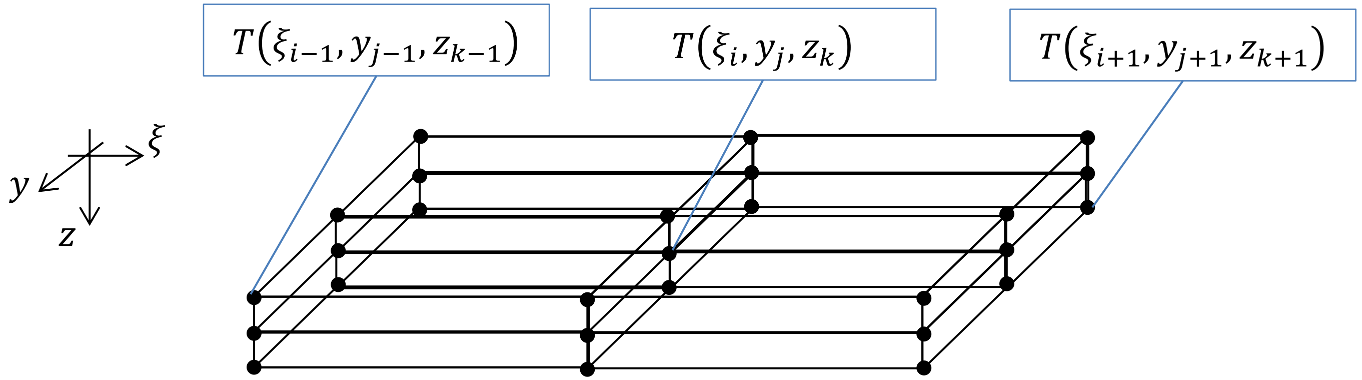
Results analysis

Thermal model – Implementation

How to implement analytical model in a numerical code?

We need to calculate the temperature in different positions of our domain

$$\boxed{T(\xi_i, y_j, z_k)\forall\, i, j, k}$$



→ I need to initialize different vectors which determine all the positions in the domain where I want to solve the equation

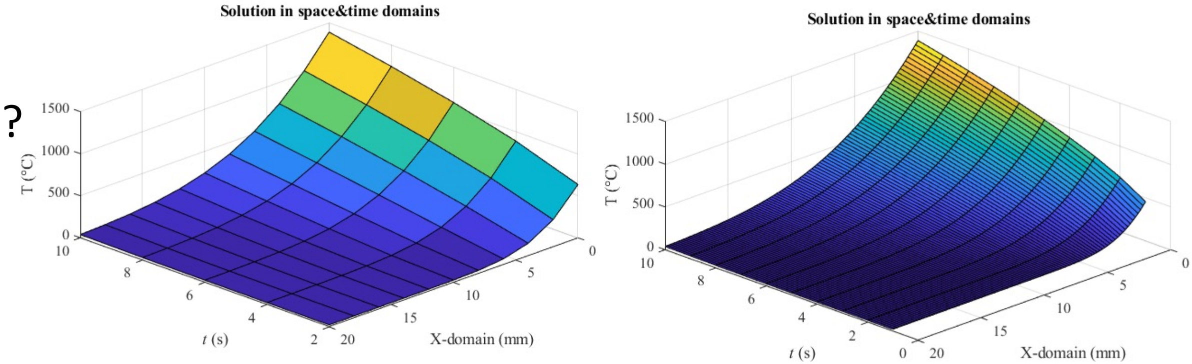
Thermal model – Implementation

2 main variables

- Extent of domain
- Resolution of domain

Appropriate choice required → Computational efficiency vs accuracy

What is the expected spatial extent?
What is the resolution required?



- From experience we can expect spatial domain in the order of 1 mm.
- Resolution usually 2 orders of magnitude smaller.
- Useful to start with fast simulation then increase computational load.
- Restrict domain to required needs (i.e. do I need to calculate for all dimensions?)

Example

<u>Fixed simulation domain</u>

$$\xi \epsilon \, [-1000{,}50]$$
$$y \epsilon \, [-200{,}200]$$
$$z \epsilon [0{,}20]$$

<u>Case 1</u>

$$\Delta\xi, \Delta y, \Delta z = 10\mu m$$
$$t_{calc} = 1.497219 \text{ s}$$

<u>Case 2</u>

$$\Delta\xi, \Delta y, \Delta z = 1\mu m$$
$$t_{calc} = 2.436115 \text{ s}$$

Thermal model implementation

Calculation of track width

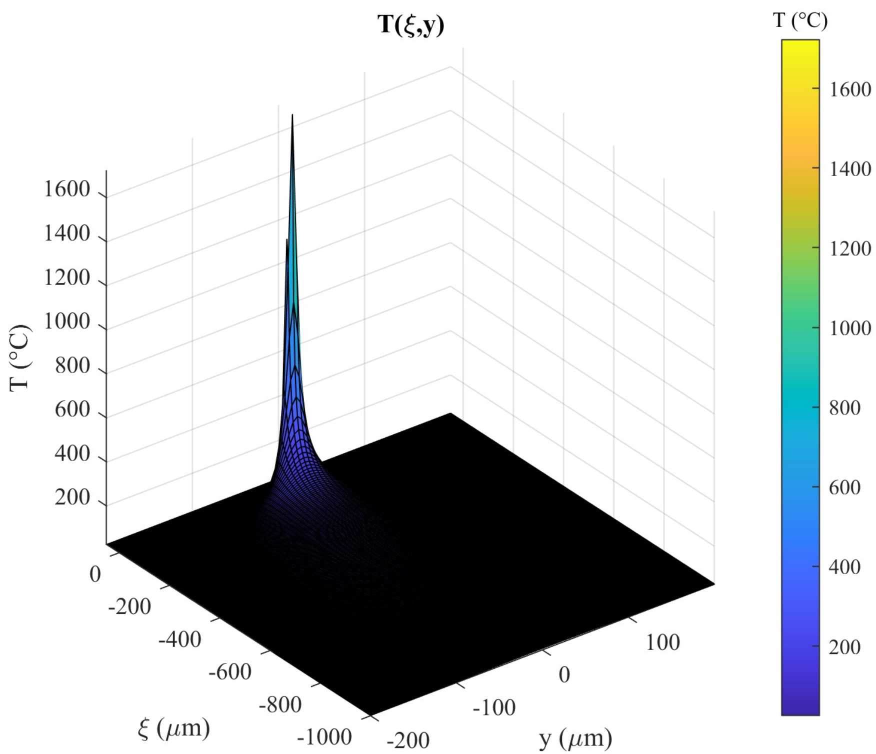
Useful Matlab functions:

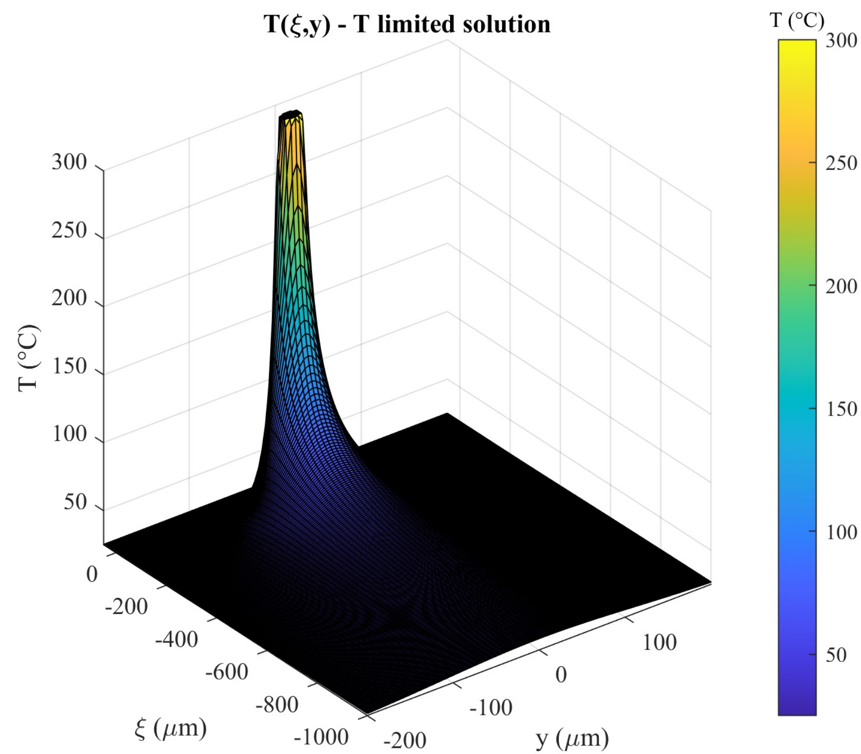
`for` [for loop to repeat specified number of times - MATLAB for - MathWorks Italia]

`surf` [Surface plot - MATLAB surf - MathWorks Italia]

Thermal model – Example results

Example of calculated temperature fields

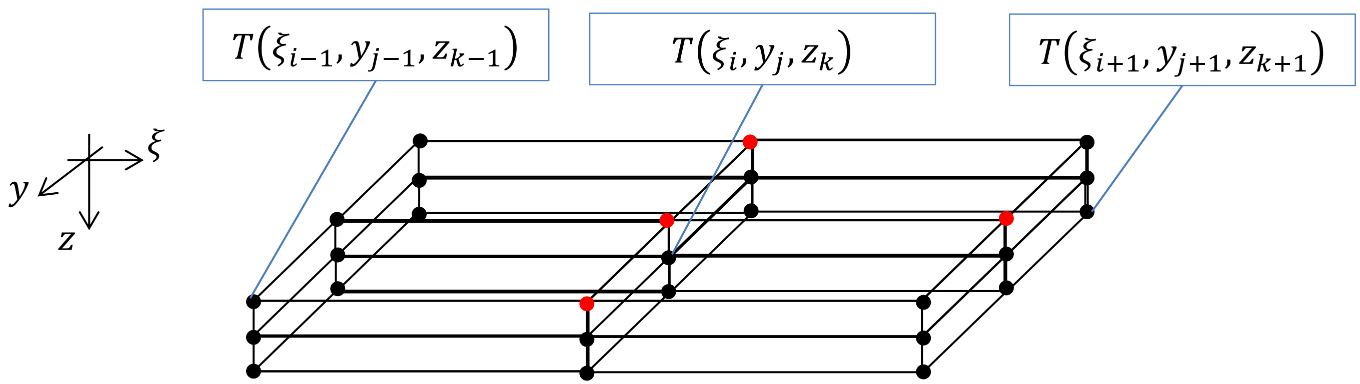




Calculation of track width

From our Temperature matrix we can estimate the vaporized material
$T(\bar{\xi}, \bar{y}, \bar{z}) \rightarrow w_{VAP}$ where $T(\xi_i, y_j, z_k) > T_{VAP}$

Example:



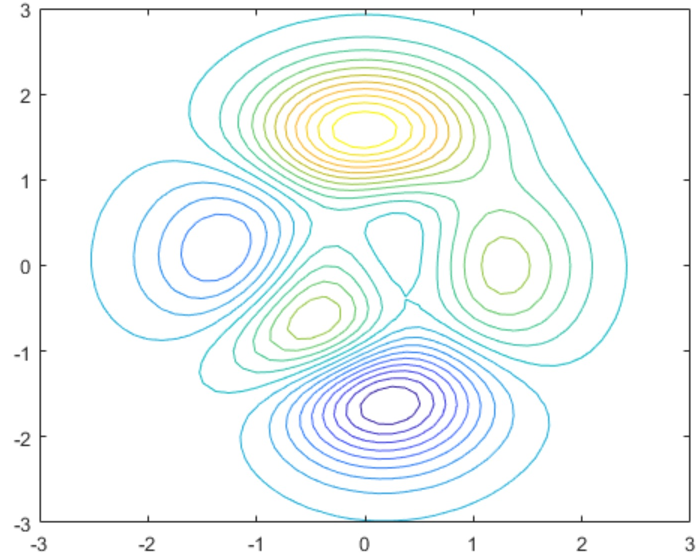
- Positions where $T(\xi_i, y_j, z_k) < T_{VAP}$
- Positions where $T(\xi_i, y_j, z_k) > T_{VAP}$

Calculation of track width

Useful Matlab functions:

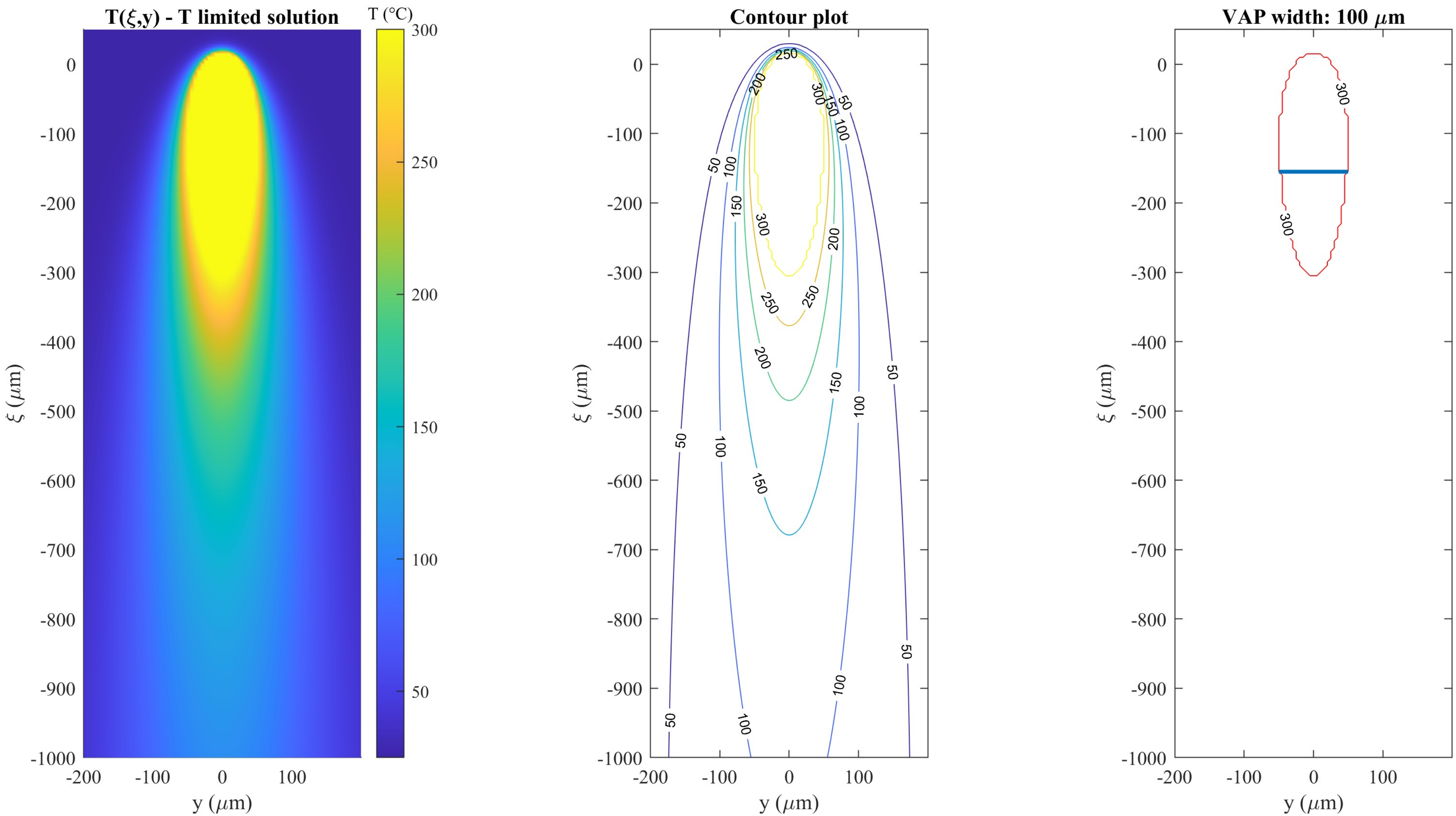
`contour` [Contour plot of matrix - MATLAB contour - MathWorks Italia]

The contour function can also give in output the values of a certain contour value (for example the vaporisation temperature…)

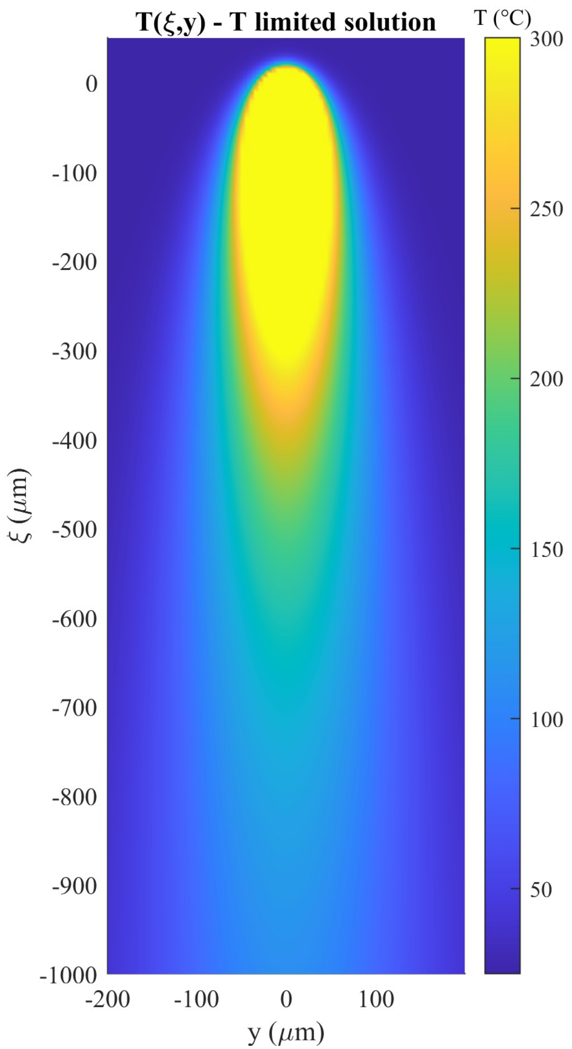


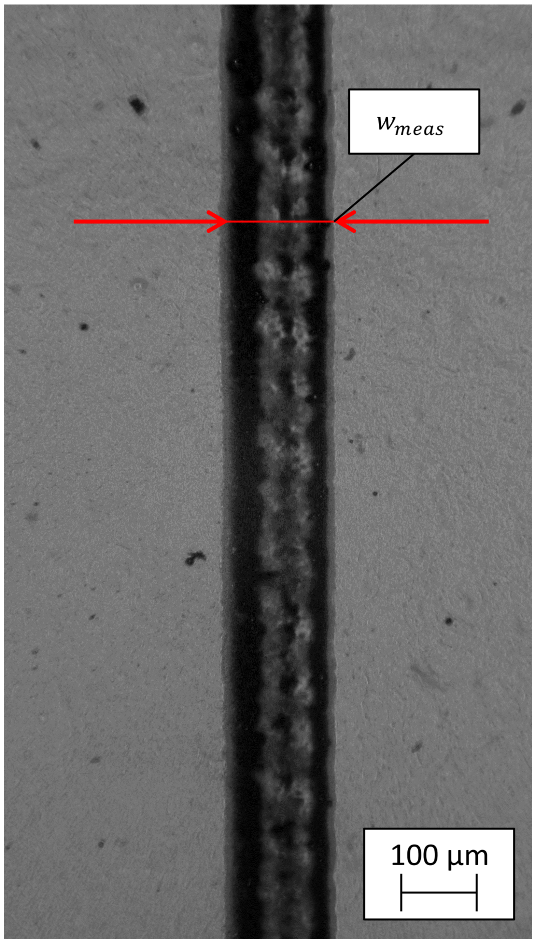
Thermal model – Example results

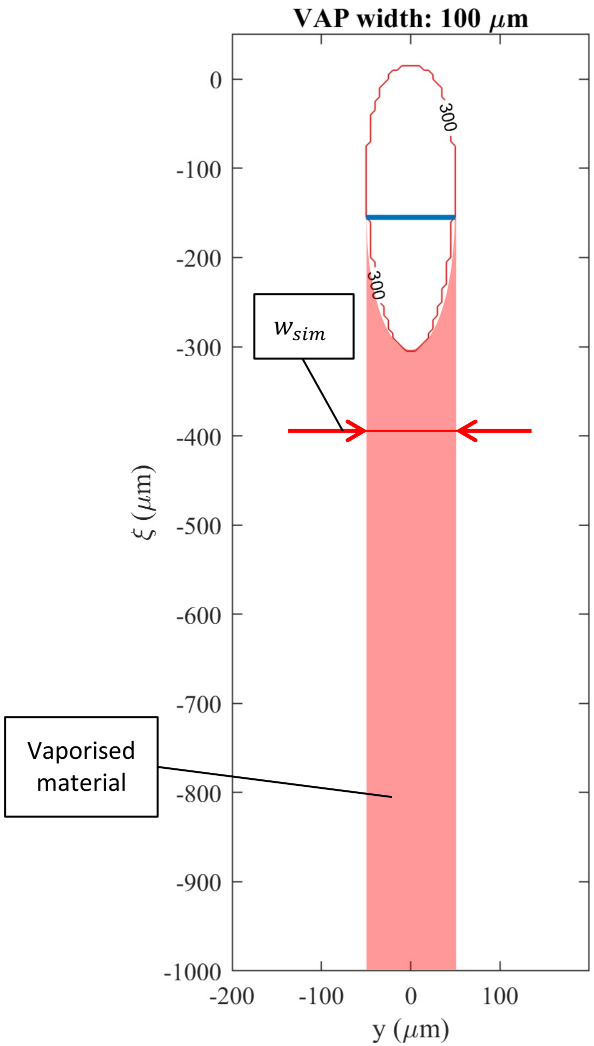
Calculation of track width



Calculation of track width vs measured track width







Thermal model implementation

Calibration of process efficiency

It is clear that the value of η we use affects our mathematical solution

→ we can use experimental data to calibrate it!

With the analytical model we can calculate parameters that otherwise we would not be able to measure.

For example:

- Penetration depth → Useful for the laboratory project!
- Cooling rate $\frac{\partial T}{\partial t}$
- Cooling gradients $\frac{\partial T}{\partial x}, \frac{\partial T}{\partial y}, \frac{\partial T}{\partial z}$

Thermal model implementation

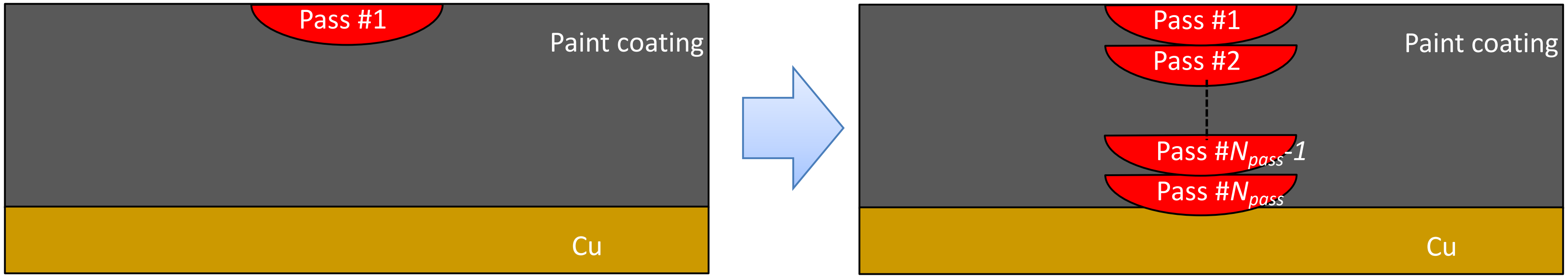
Comparison with laboratory experiments

Track width smaller than theoretical value!

→ $\eta<1$

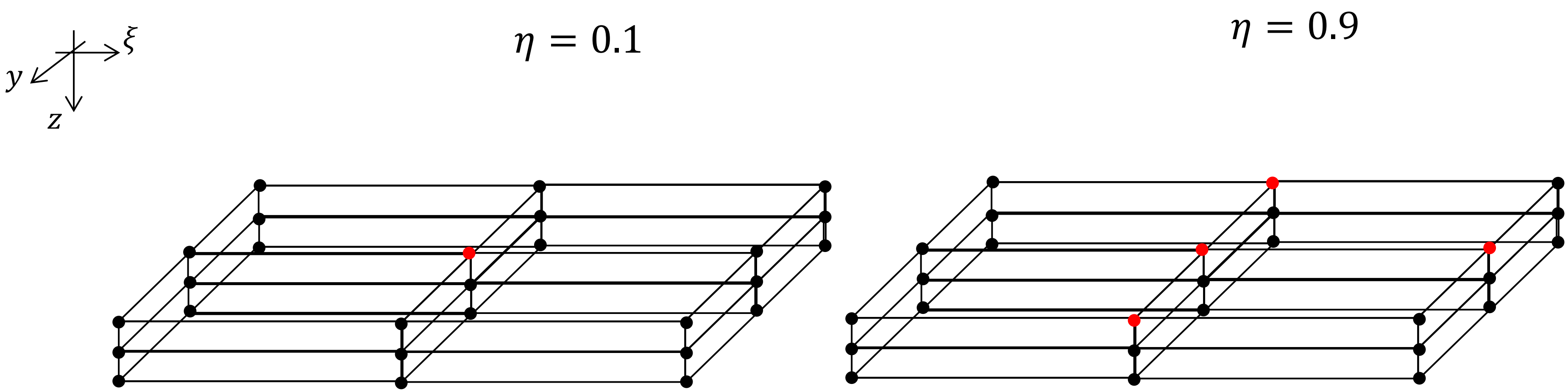
Minimisation problem to calibrate efficiency coefficient based on experimental data

Once the model is calibrated
→ possible to estimate penetration depth & number of passes required



Thermal model implementation

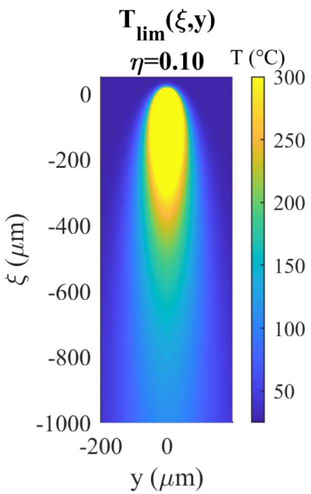
Calibration of process efficiency

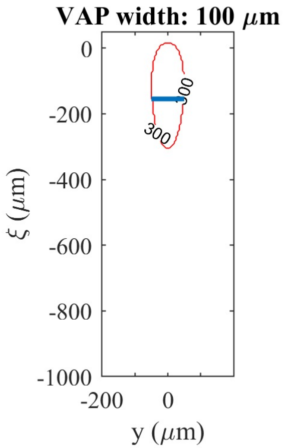


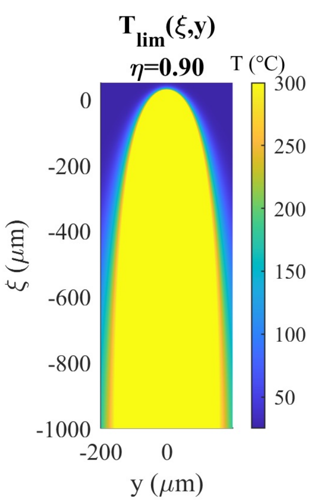
- Positions where $T(\xi_i, y_j, z_k) < T_{VAP}$ (black dots)
- Positions where $T(\xi_i, y_j, z_k) > T_{VAP}$ (red dots)

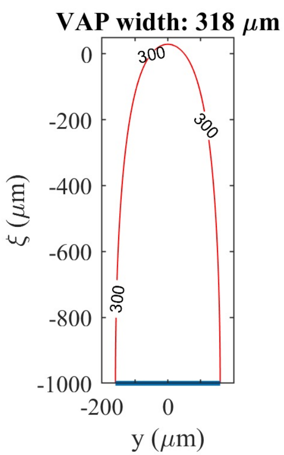
Thermal model – Example results

Calibration of process efficiency









Thermal model implementation

Calibration of process efficiency

We need to approximate our solution to our experimental measurements

$$w_{simulation} \neq w_{measured}$$

→implement an error minimization algorithm

A numerical approach is effective since we do not have a linear relationship between η and $w_{simulation}$

Let's define the relative error:

$$err(\%) = \frac{|w_{simulation} - w_{measured}|}{w_{measured}}$$

We define also our temperature distribution matrix independent of the ambient T:

$$T^*(\bar{x}, \bar{y}, \bar{z}) = T(\bar{x}, \bar{y}, \bar{z}) - T_0$$

Calibration of process efficiency

For increasing values of η calculate the track width:

$\forall\, i$

$$T_{tmp}(\bar{x},\bar{y},\bar{z}) = T^*(\bar{x},\bar{y},\bar{z}) \cdot \eta_i + T_0$$

$\rightarrow w_{sim,i}$

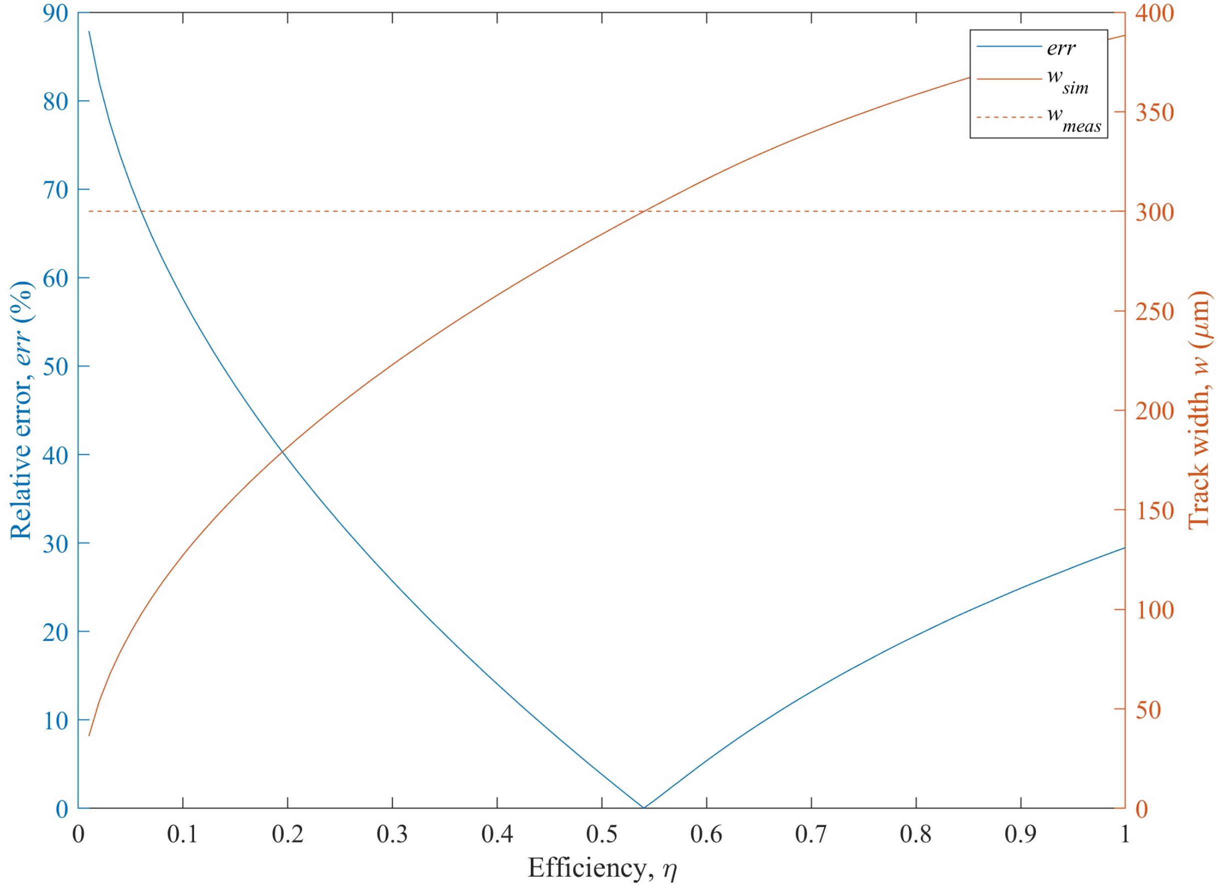
$\rightarrow e_i$

Once obtained the error vector apply an algorithm to numerically identify the minimum (we can even consider `min` [Minimum elements of an array - MATLAB min - MathWorks Italia])

Tip: Once obtained the temperature matrix $T^*(\bar{x},\bar{y},\bar{z})$ you are not required to calculate all over again the code but you may calculate a temporary temperature matrix $T_{tmp}(\bar{x},\bar{y},\bar{z})$

Thermal model – Example results

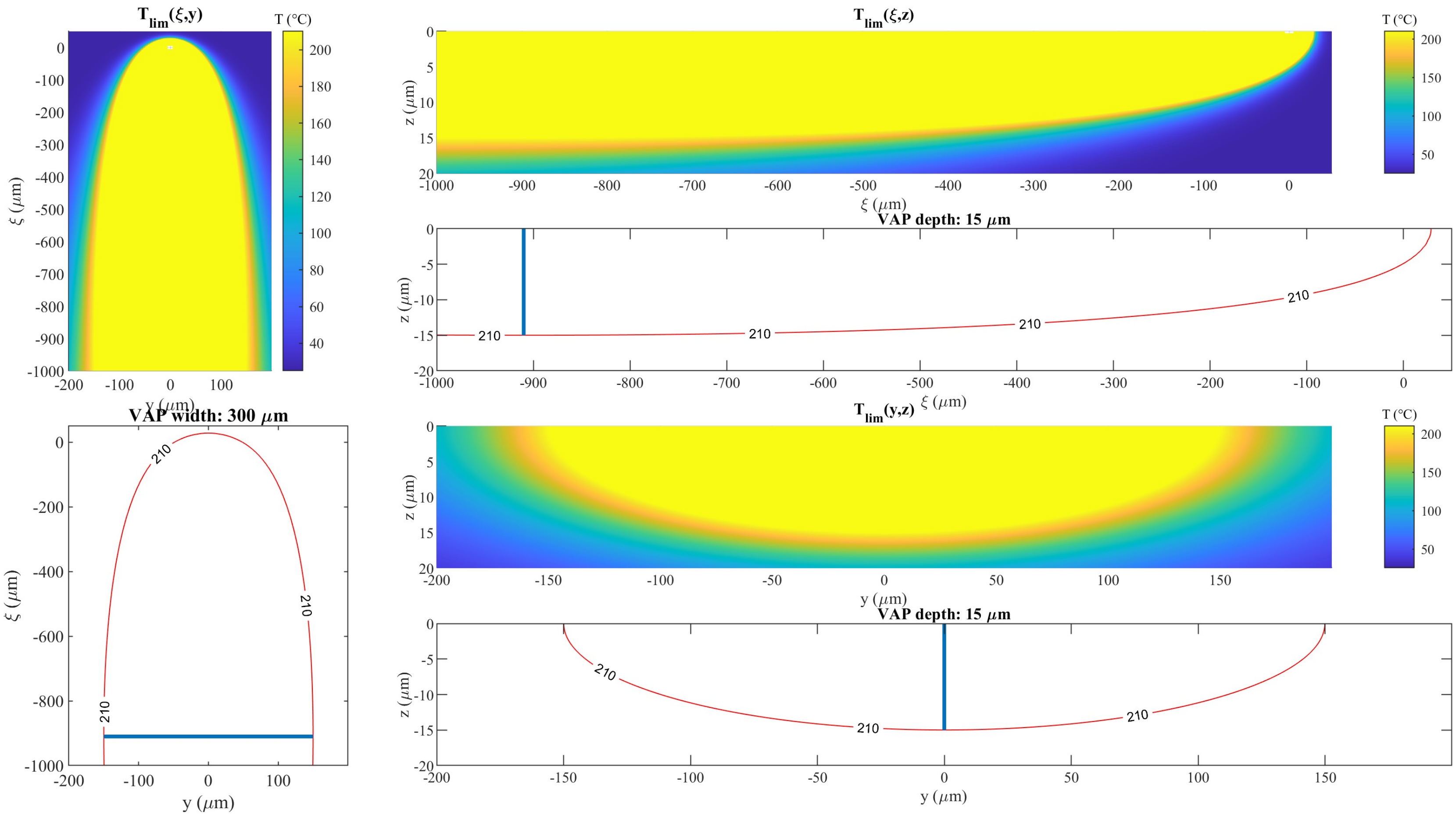
Calibration of process efficiency



→Once η is calibrated we can estimate the penetration depth using the same approach employed for the track width calculation

Thermal model – Example results

Estimation of penetration depth



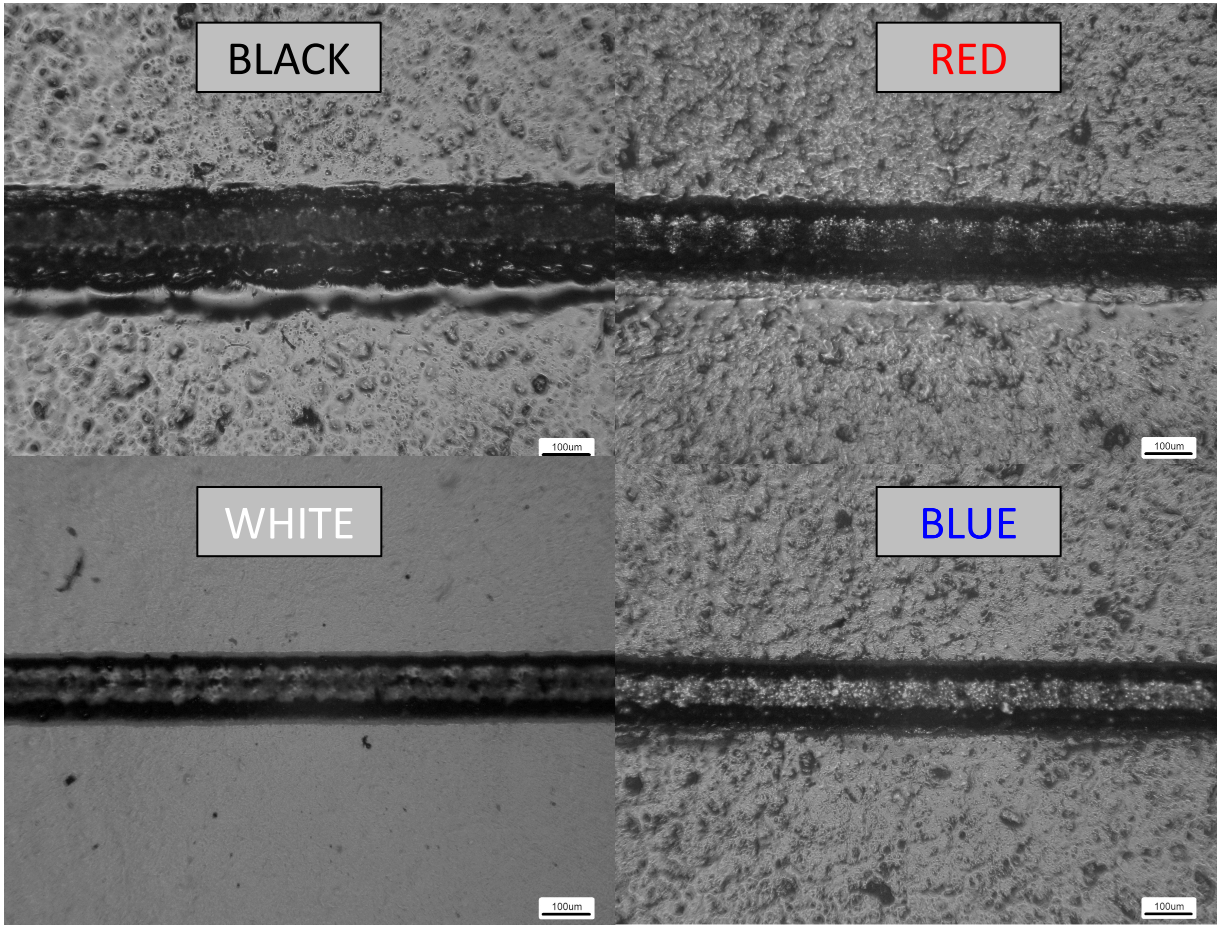
Experimental data

Fixed factors	
Power, *P* (mW)	1600
Emission wavelength, λ (nm)	445
Focus position, *f* (mm)	0
N° of passes	1
Feed rate, *v* (mm/min)	800
Variable factors	
Paint coating colour	RED – BLUE – BLACK - WHITE

	Track width, w_{meas} (µm)			
Meas #	Black	White	Red	Blue
1	172	133	136	129
2	163	129	144	132
3	177	135	138	124
4	177	135	132	128
5	165	128	137	122

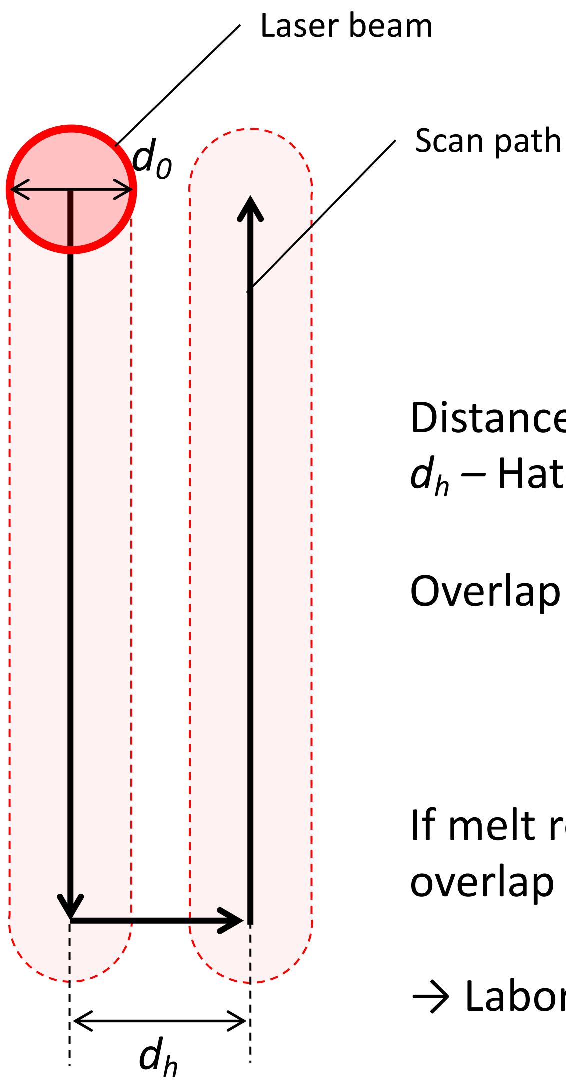
Results from single track experiments

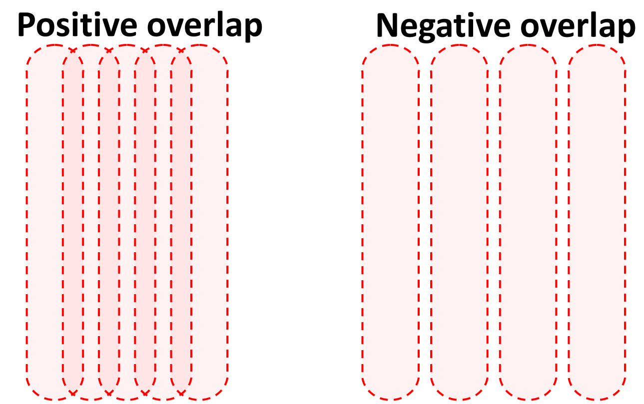
5 track width measurements (w_{meas}) per single track



Large area processing

Theoretical concept





Distance between adjacent scan tracks:
d_h – Hatch distance

Overlap O_h

$$O_h(\%) = \frac{d_0 - d_h}{d_0}$$

If melt region > beam waist diameter d_0 we can have negative overlap to process large areas

→ Laboratory experiments required to determine optimal overlap

Contact details

Questions?

mecc
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