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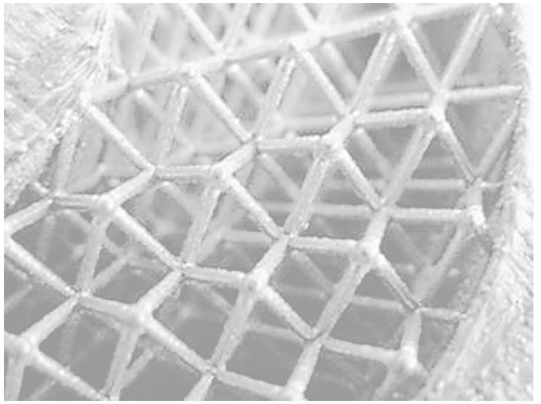
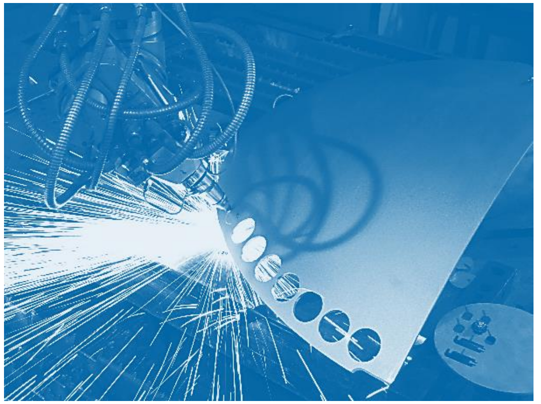


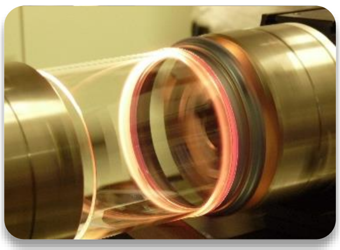
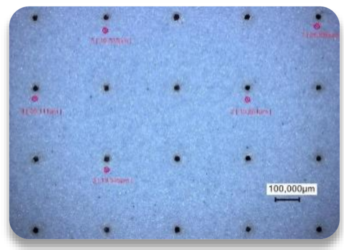
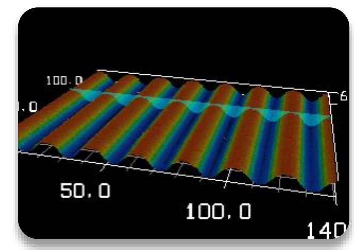


Understanding and Optimization of ultra-short pulse laser ablation of technical ceramics based on experimental data

Maria Friedrich

WOST 2019 – Weimarer Optimierungs- und Stochastiktage

Laser processing of glass and ceramics

Joining	Polishing	Cutting	Marking	Structuring
				
				

← High thermal influence

High resolution / precision →

CO_2 laser → Solid state laser → Fiber laser → USP laser

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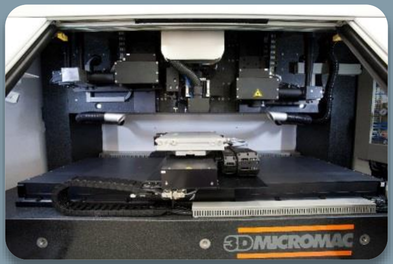
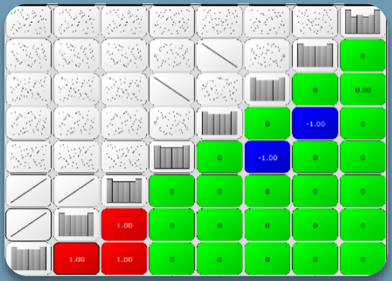
Outline

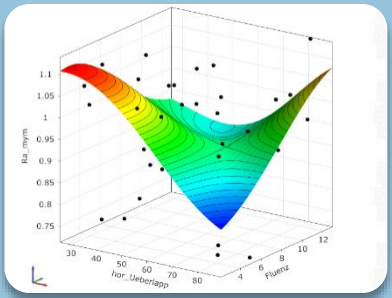
1. Experimental Approach



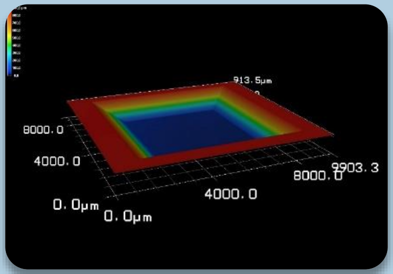
2. Design of Experiments



3. Sensitivity Analysis



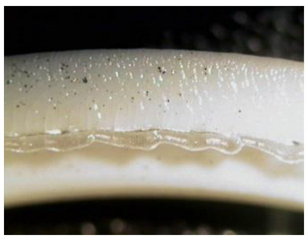
4. Industrial Applications



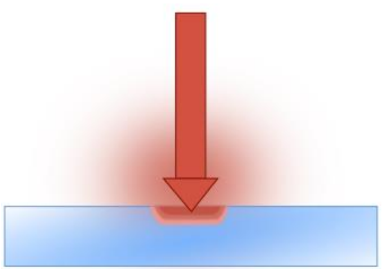
1. Experimental Approach

CO_2 laser → Solid state laser → Fiber laser → USP laser

λ = 10,6 µm

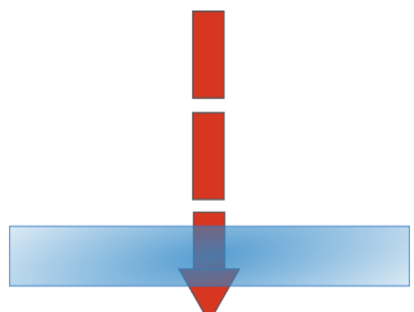


- Thermally affected process
- Melting of material

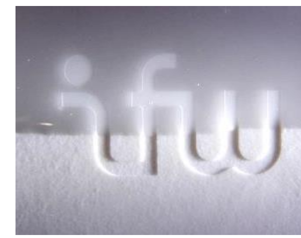


λ = 1064 nm

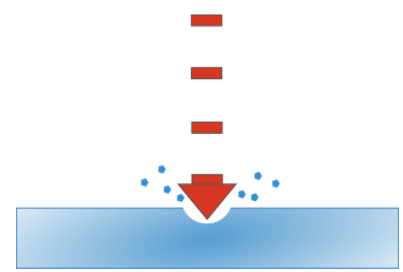
- Redeposited material, cracks
- OR: material transparent



λ = 1064 nm, **τ_p < 10 ps**



- Non-linear absorption
- Thermal conduction negligible
- Precise material removal



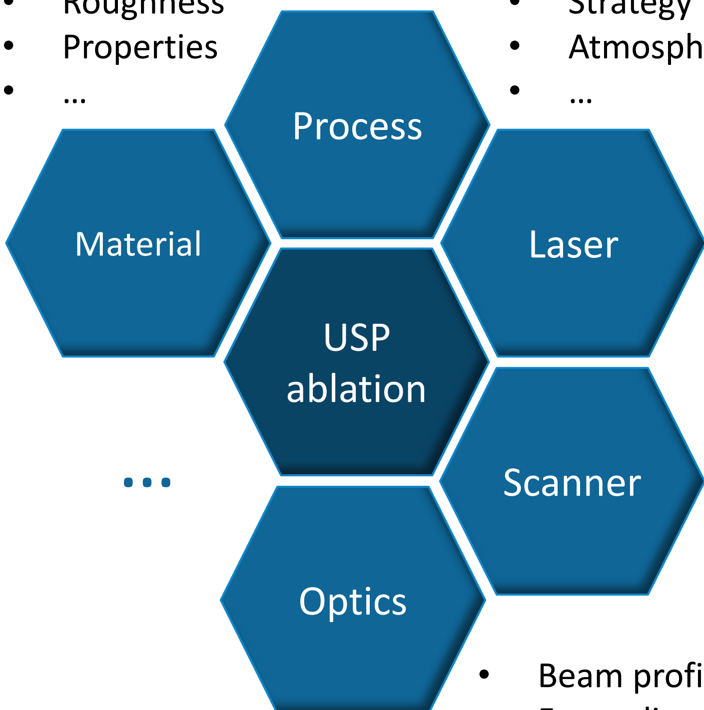
1. Experimental Approach

Process Parameters

Multitude of process parameters …

- Roughness
- Properties
- …

- Strategy
- Atmosphere
- …

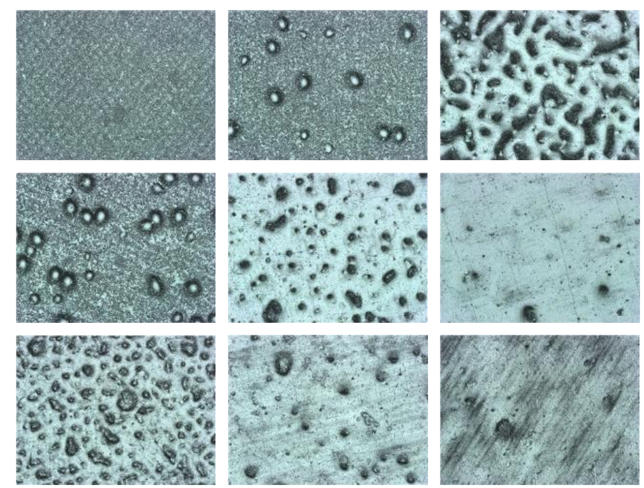


- Wavelength
- Pulse duration
- Pulse energy
- Repetition rate
- …

- Marking speed
- Line distance
- Pulse overlap
- Number of layers
- …

- Beam profile
- Focus diameter
- Divergence
- …

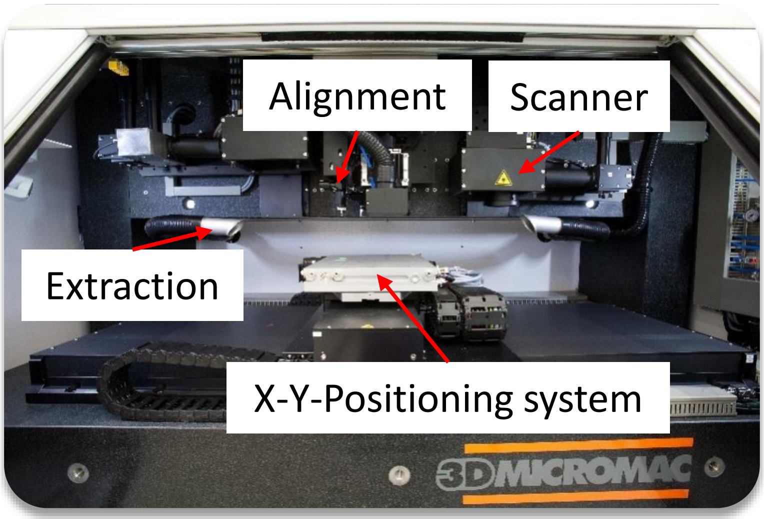
… results in various surface qualities



1. Experimental Approach

Multi-dimensional parameter space

→ Value ranges are unevenly distributed



- Wavelength: 1064 nm, 532 nm, 355 nm
- Pulse duration: 230 fs – 10 ps
- Repetition rate: < 1 MHz
- Max. power: 25 W

Power P [W]

	Min	Max
IR	0	24
VIS	0	12
UV	0	6

Fluence (Energy density) F [J/cm²]

	Min	Max
IR	0	15
VIS	0	35
UV	0	30

Pulse Overlap O_h [%]

	Min	Max
IR	50	99
VIS	-10	99
UV	-30	99

1. Experimental Approach

Procedure

Multi-dimensional parameter space

→ Sensitivity analysis, meta model, optimization
→ Identification of main parameters and non-linear effects

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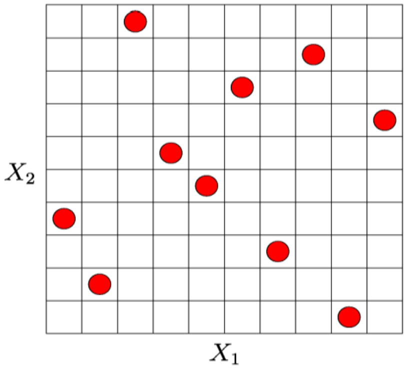
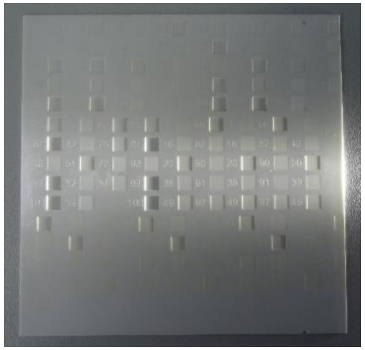
DoE

Latin Hypercube Sampling



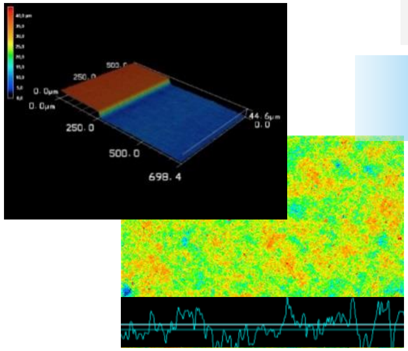
Experiments

USP ablation of alumina (Al_2O_3)



Measurement

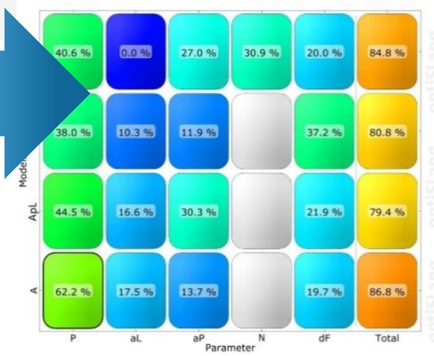
Roughness, Ablation depth



Excel Add-In

Analysis

Sensitivity analysis based on MOP



2. Design of Experiments

DoE 1.0

- Use of widest possible parameter range within the process window of one material
- Aim: identification of main parameters

INPUTS

- Wavelength: λ = 355 / 532 / 1064 nm
- Focal length: f = 40 / 100 / 250 mm
- Focus diameter: d_f = 11 … 110 µm
- Number of Designs: 100

- Experimental Design according to native parameters
  - ➢ Power P
  - ➢ Line distance a_L
  - ➢ Pulse distance a_P

d_f →

DoE 3.0

- Restriction to a few parameters
- Aim: maximum increase of model quality, good comparability of different materials

INPUTS

- Wavelength: λ = 532 nm = const.
- Focal length: f = 100 mm = const.
- Focus diameter: d_f = 14 µm = const.
- Number of Designs: 50

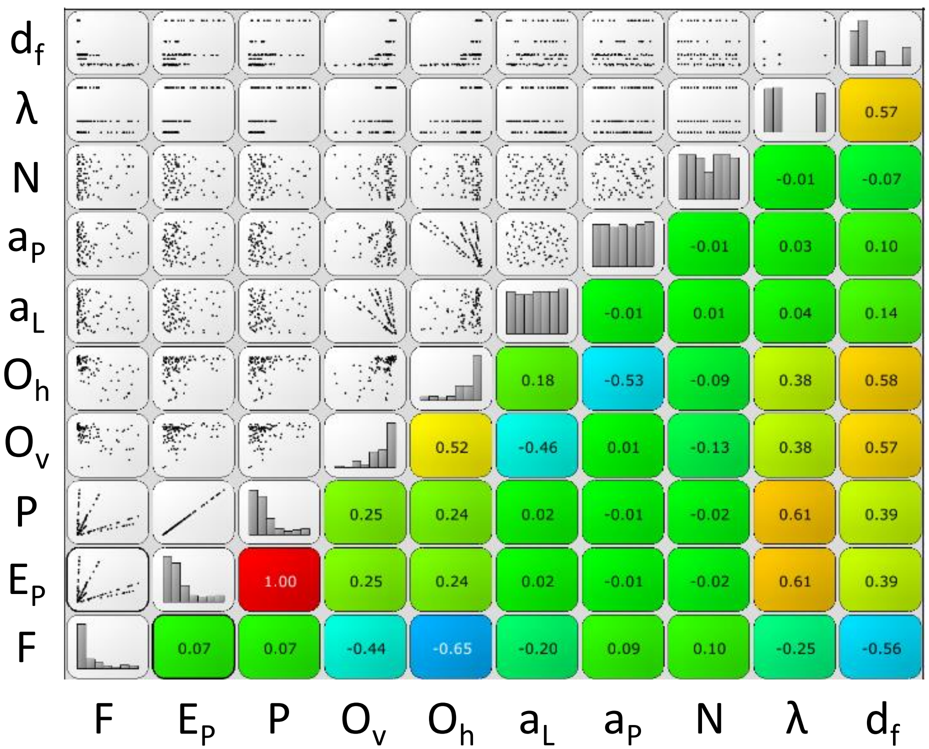
- Experimental Design according to derived parameters
  - ➢ Fluence F
  - ➢ Vertical pulse overlap O_v
  - ➢ Horizontal pulse overlap O_h

2. Design of Experiments

Correlation Matrix

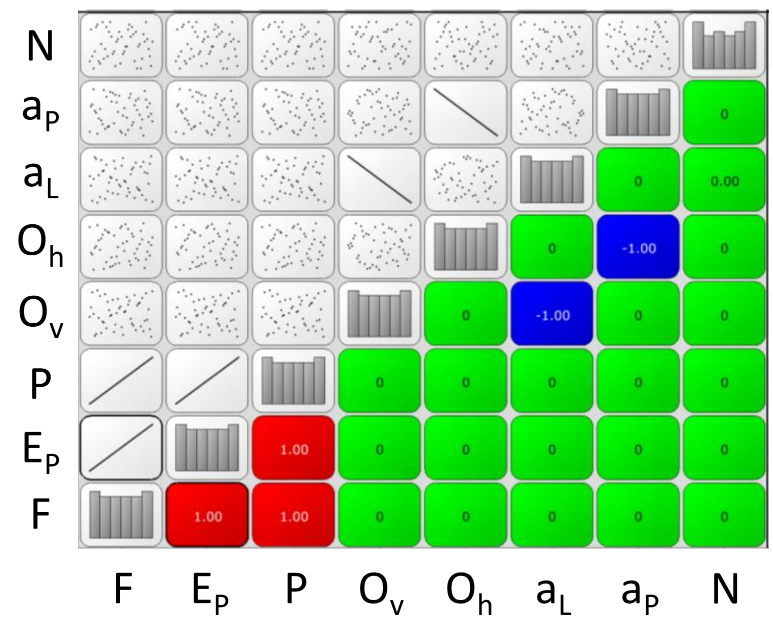
DoE 1.0

- Use of widest possible parameter range within the process window of one material
- Aim: identification of main parameters



DoE 3.0

- Restriction to a few parameters
- Aim: maximum increase of model quality, good comparability of different materials



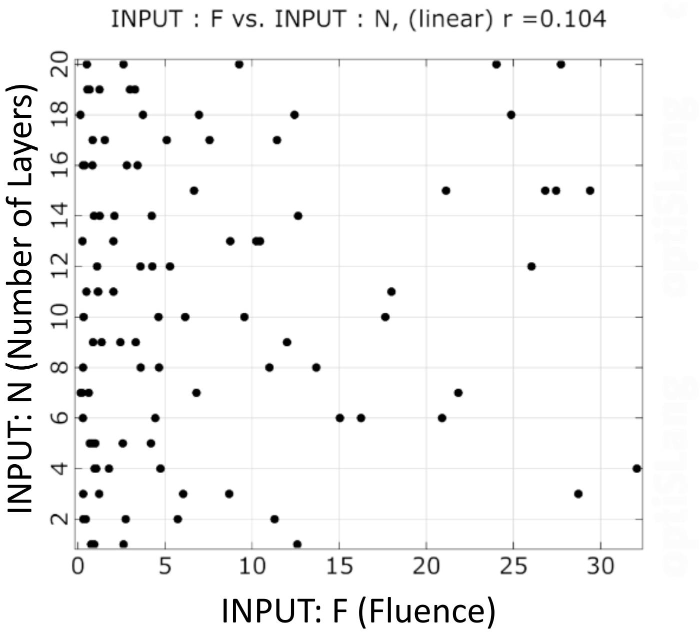
→ Avoidance of input correlations

2. Design of Experiments

Anthill Plots

DoE 1.0

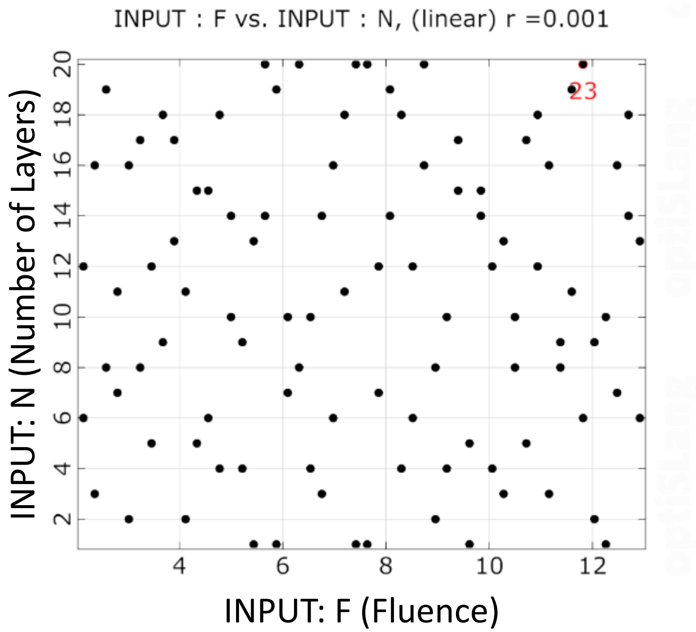
- Use of widest possible parameter range within the process window of one material
- Aim: identification of main parameters



→ Asymmetric distribution, even of independent parameters

DoE 3.0

- Restriction to a few parameters
- Aim: maximum increase of model quality, good comparability of different materials



→ Symmetrical distribution of all parameters

2. Design of Experiments

Coefficient of Prognosis

DoE 1.0

- Use of widest possible parameter range within the process window of one material
- Aim: identification of main parameters

	P	a_L	a_P	N	d_f	Total
Time *t*		66.5 %	3.9 %	43.0 %		96.5 %
t_A / N	44.9 %	14.5 %	29.3 %		23.4 %	77.5 %
Rate *r*	67.9 %	20.1 %	18.0 %		23.3 %	86.4 %
Depth t_A	37.7 %	0.0 %	26.6 %	27.2 %	21.2 %	86.4 %
Roughness *Ra*	33.0 %	11.3 %	2.6 %		36.9 %	78.0 %

→ Good roughness model due to large value range (*Ra* = 0,4 … 3,8 µm)

DoE 3.0

- Restriction to a few parameters
- Aim: maximum increase of model quality, good comparability of different materials

	F	O_V	O_h	N	Total
Time *t*		78.5 %	46.5 %	49.0 %	99.3 %
t_A / N	38.2 %	31.0 %	29.9 %		93.3 %
Rate *r*	65.0 %	14.7 %	34.1 %		95.4 %
Depth t_A	22.6 %	21.4 %	22.8 %	32.2 %	92.4 %
Roughness *Ra*	35.4 %				35.4 %

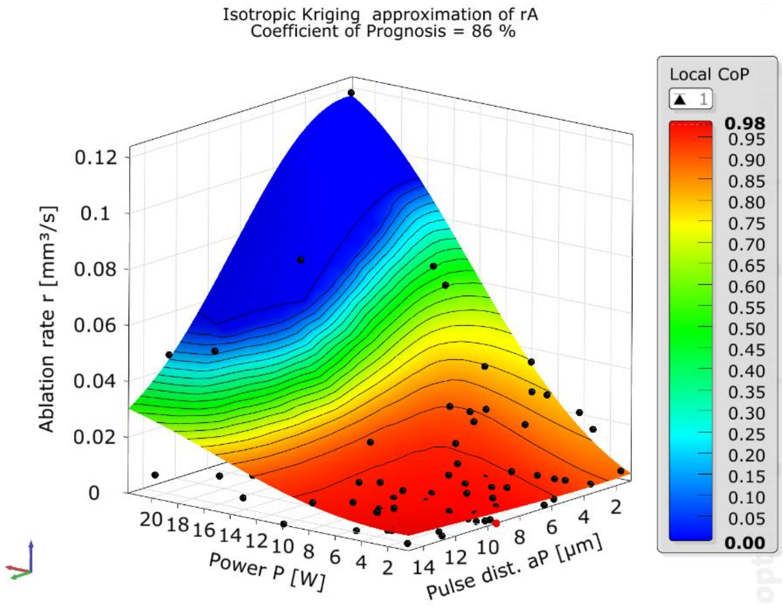
→ Weak roughness model (*Ra* = 0,5 … 1,1 µm)
→ Good models for depth-related parameters

2. Design of Experiments

Coefficient of Prognosis

DoE 1.0

- Use of widest possible parameter range within the process window of one material
- Aim: identification of main parameters



→ Good roughness model due to large value range (*Ra* = 0,4 … 3,8 µm)

DoE 3.0

- Restriction to a few parameters
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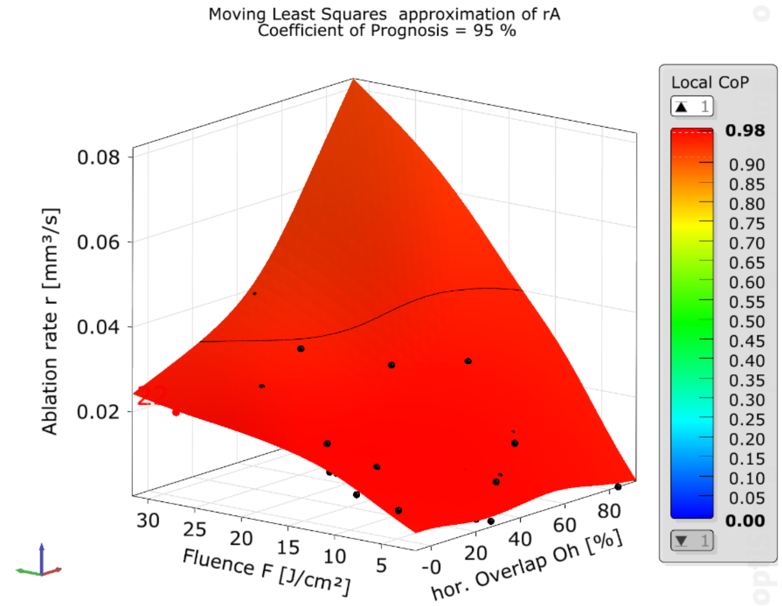


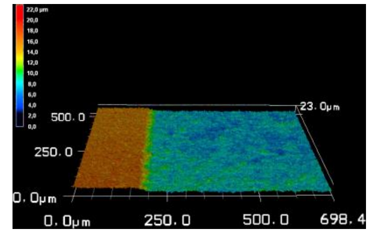
→ Weak roughness model (*Ra* = 0,5 … 1,1 µm)
→ Good models for depth-related parameters

3. Sensitivity Analysis

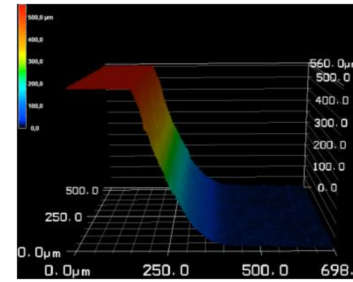
Ablation rate

- Ablation rate increases with power
- Line distance and pulse distance interact
  → High values: high speed
  → Small values: high material removal

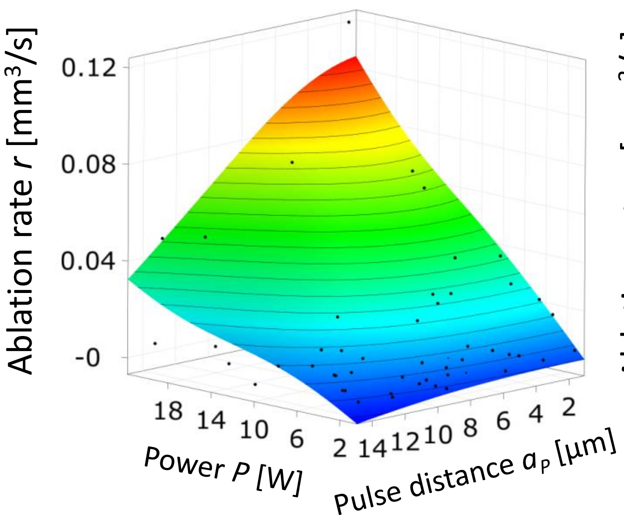
Al_2O_3:

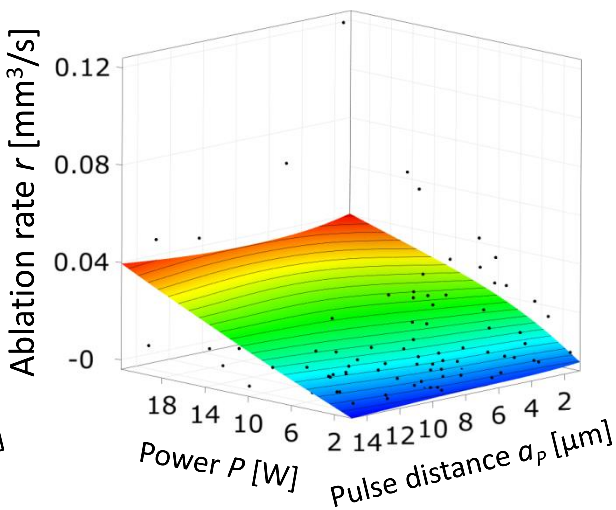


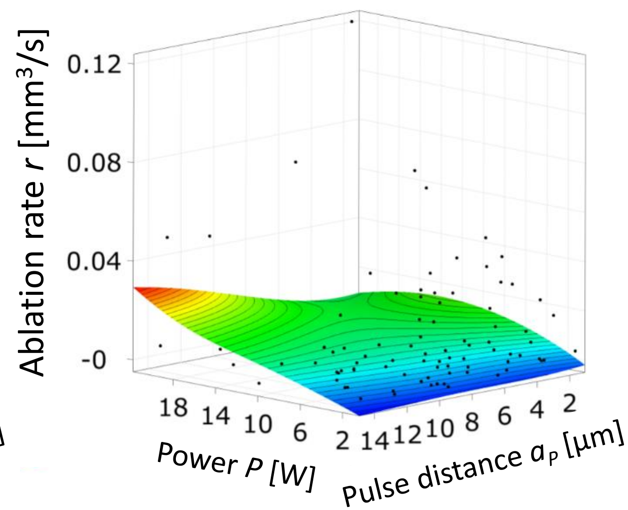
$r_{min} \approx 0$ mm³/min



$r_{max} = 7.8$ mm³/min







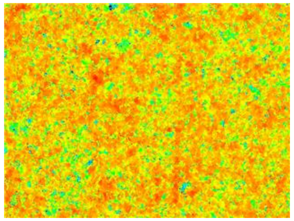
Line distance: $a_L = 15$ µm | $a_L = 4.4$ µm | $a_L = 1$ µm

3. Sensitivity Analysis

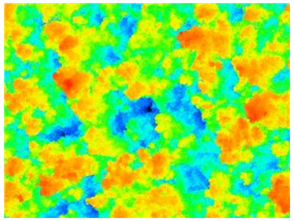
Roughness

- In general: roughness increases with fluence
- Optimal pulse overlap depends on fluence
- With increasing fluence: minimum shifts to smaller values

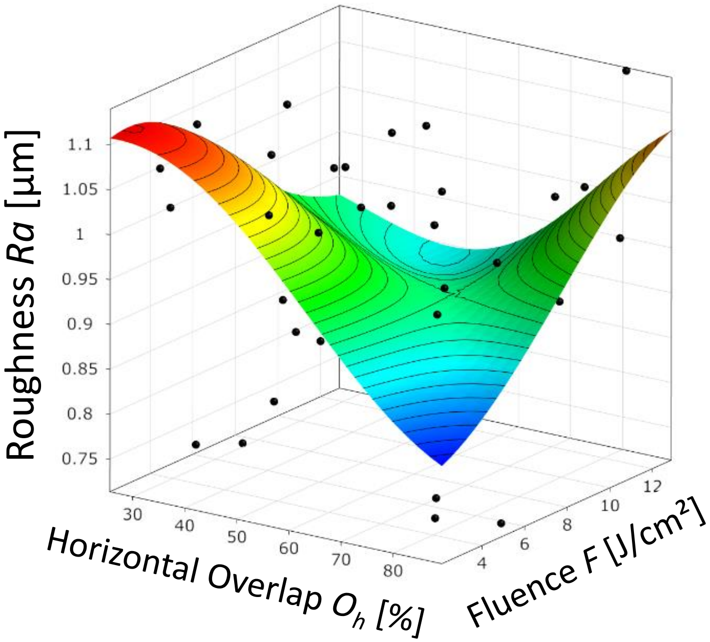
Al_2O_3:

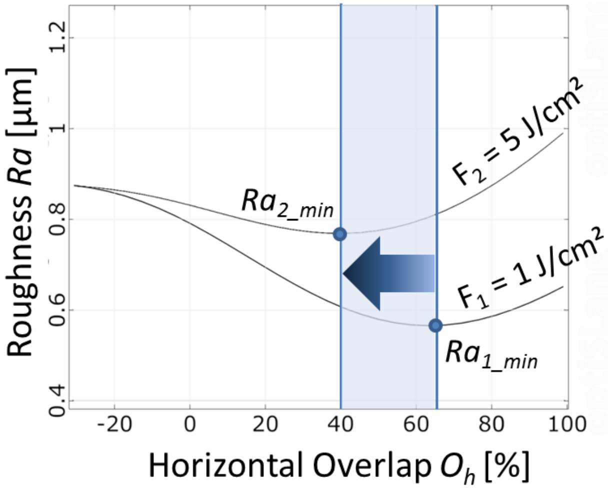


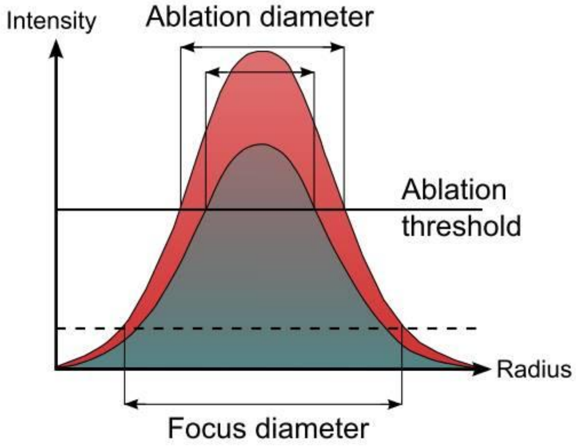
Ra_{min} = 0,42 µm



Ra_{max} = 3,8 µm







3. Sensitivity Analysis

Different materials

- Transfer of DoE 3.0 to other materials (LTCC, AlN, Porcelain)
- Use of “Space filling Latin Hypercube Sampling”

DP 951

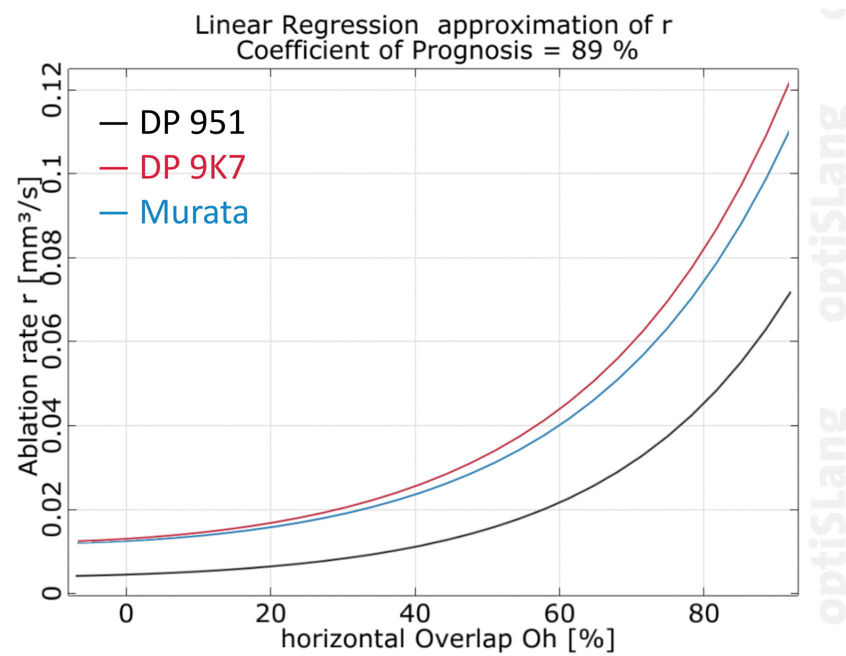
	N	F	O_h	O_v	Total
r	0.0 %	27.4 %	80.7 %		94.7 %
t_A	18.7 %	16.1 %	61.4 %	22.2 %	93.1 %
Ra	44.2 %		67.0 %		73.3 %

DP 9K7

	N	F	O_h	O_v	Total
r	1.5 %	44.5 %	53.8 %	2.3 %	89.6 %
t_A	32.6 %	28.2 %	47.4 %	23.3 %	96.4 %
Ra		16.2 %	56.2 %	7.3 %	84.8 %

Murata

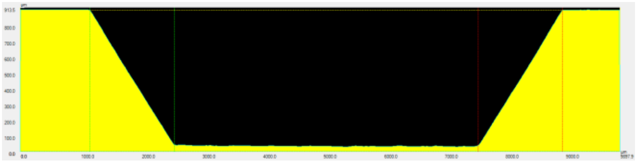
	N	F	O_h	O_v	Total
r		48.7 %	42.5 %		84.6 %
t_A	30.3 %	23.2 %	31.3 %	36.4 %	93.2 %
Ra	13.8 %	21.9 %	46.6 %	31.9 %	67.7 %

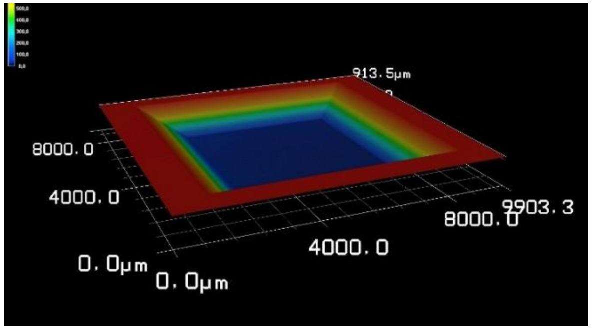


→ Similar materials can be combined to one model
→ Model quality stays the same

4. Industrial Applications

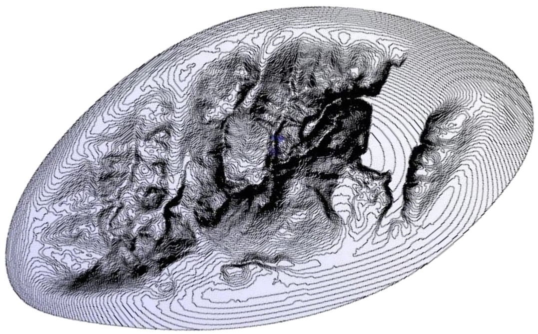
- Microsystems technology: fabrication of precise cavities in Al_2O_3 / LTCC for the positioning of microchips:
  - Profile depth: 800 µm
  - Bottom: 5 x 5 mm²
  - Flank angle: 30°

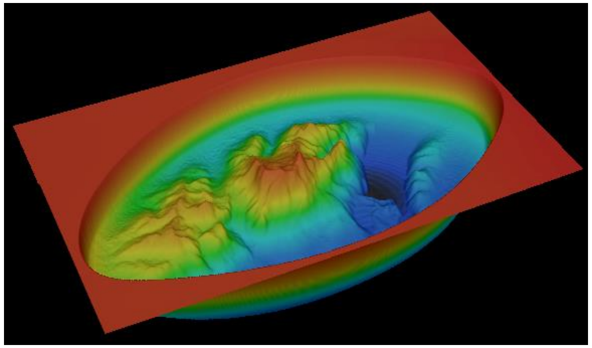




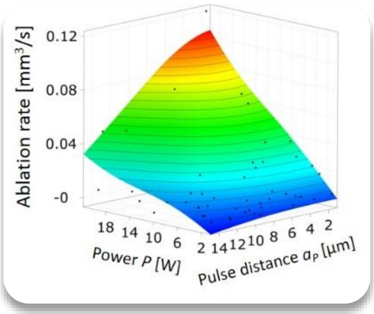
- High-value consumer goods: manufacturing of individual design structures in porcelain: Example: “Zugspitze” (ΔX = 25 mm, ΔZ = 2,1 mm)

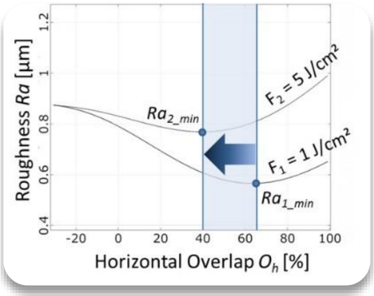
Stack of 100 layers → Ablation of negative volume → 3D freeform profile

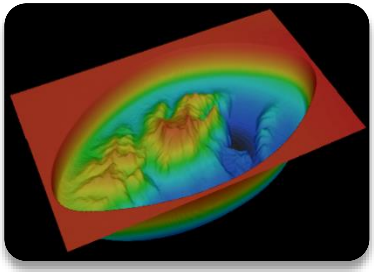




Summary







- optiSLang can be used to create physically meaningful metamodels based on experimental data
- The further development of the DoE (symmetrical parameter space, restriction to a few parameters) increased the model quality
- For a comprehensive understanding of the process, all models should be considered
  - DoE 1.0: Knowledge about whole parameter space
  - DoE 3.0: Comparison of different materials
- Native and derived parameters must be considered separately, but both provide important insights
  - Native parameters: depth-related outputs, focus diameter
  - Derived parameters: roughness-related outputs
- General question: What knowledge would you like to achieve?
  - Reduce the experimental design to provide additional insights!

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Ernst-Abbe-Hochschule Jena University of Applied Sciences

LLT Applikation Laser- und Lichtstrahl-Technologie

LUST Hybrid-Technik A member of Pankl-SHW Industries AG

Reichenbach Porzellanmanufaktur

VIA Electronic

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Thüringer Aufbaubank

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EUROPÄISCHE UNION