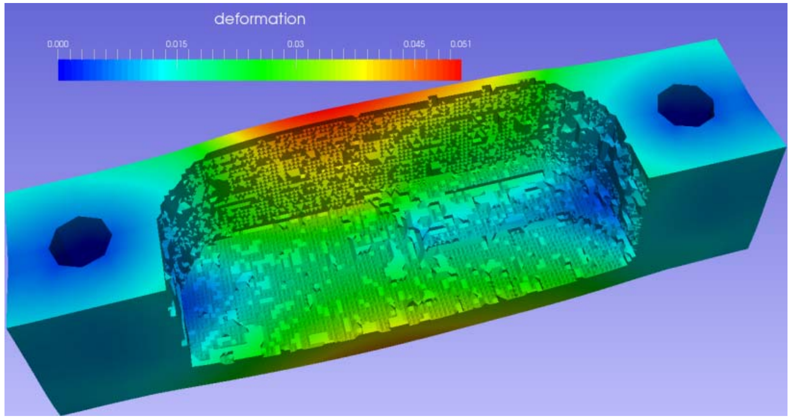
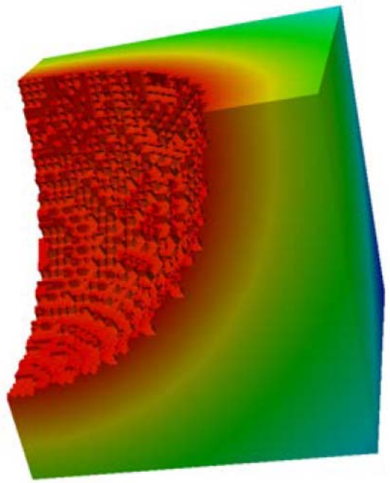
Simulation and Optimization of thermal distortions for milling processes





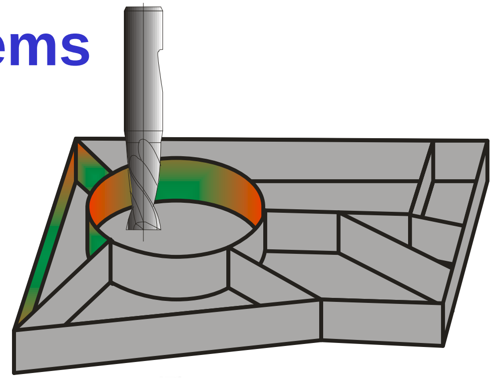
Alfred Schmidt
Center for Industrial Mathematics
and MAPEX Center for Materials and Processes
University of Bremen, Germany

Joint work with
Carsten Niebuhr (ZeTeM)
Jonathan Montalvo-Urquizo and **Maria G Villarreal-Marroquin**
(Modeling Optimization and Computing Technology SAS de CV, Monterrey, MX)

KAAS Seminar
KARLSTADS UNIVERSITET 05.09.2018

Background:

Different Modelling / simulation / optimization problems
from applications in joint projects with engineers

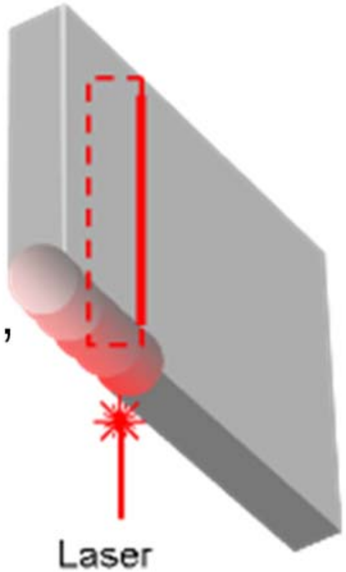


All include:

an explicit or implicit heat treatment
    parabolic heat equation

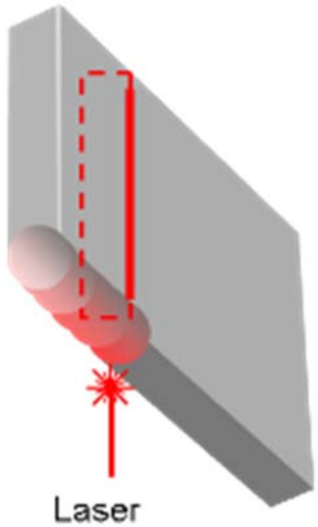
coupling with mechanics or fluidmechanics
    elliptic or elliptic/parabolic equation

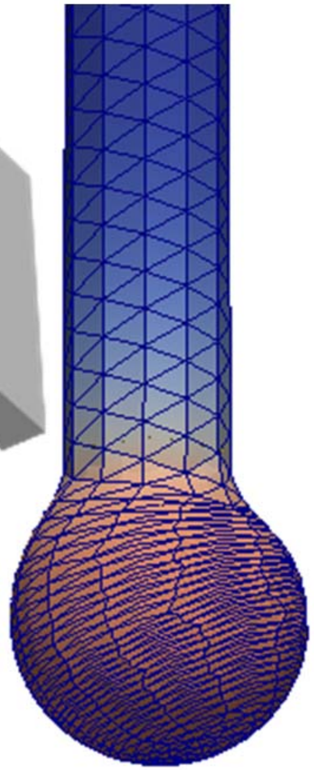
and
    time dependent domain is part of the solution,
    some other **nonlinearities** are included

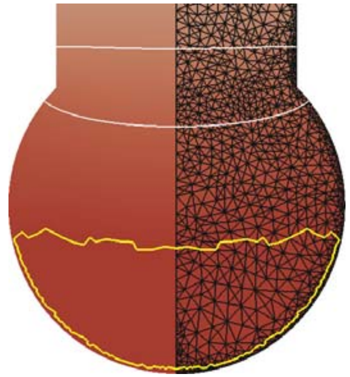


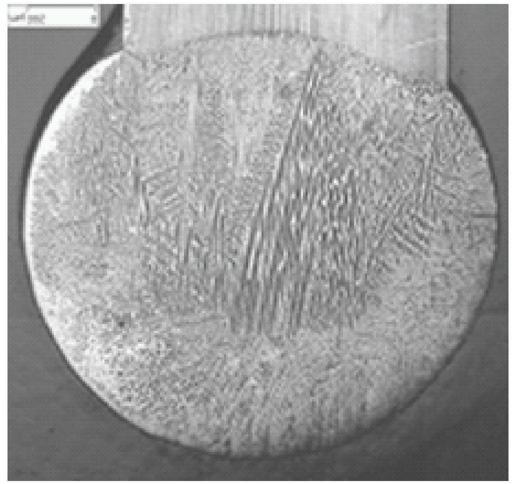
Digital product twin – production twin (– performance twin)

Application 1:
Microstructure of solification



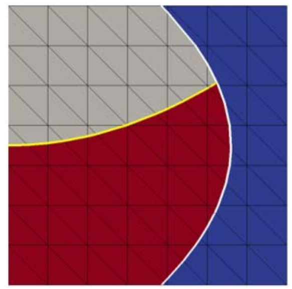






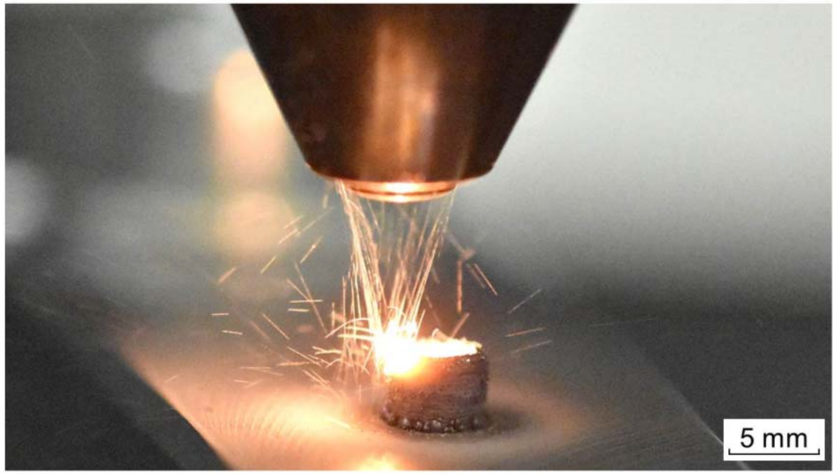
Joint work with
Mischa Jahn and Andreas Luttmann,
Heiko Brüning and Frank Vollertsen (BIAS)
Eberhard Bänsch (AM3 Erlangen)

Project in DFG Collaborative Research Centre 747 “Micro cold forming”

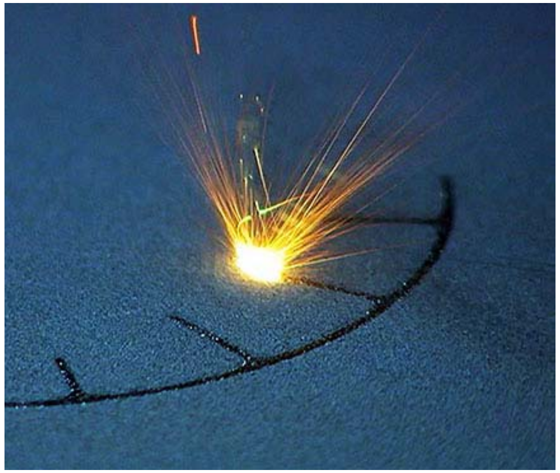


Application 2:
Phase Transitions in
Additive Manufacturing Processes (3D printing)

- Laser powder cladding
- Selective laser melting



Bohlen 2017

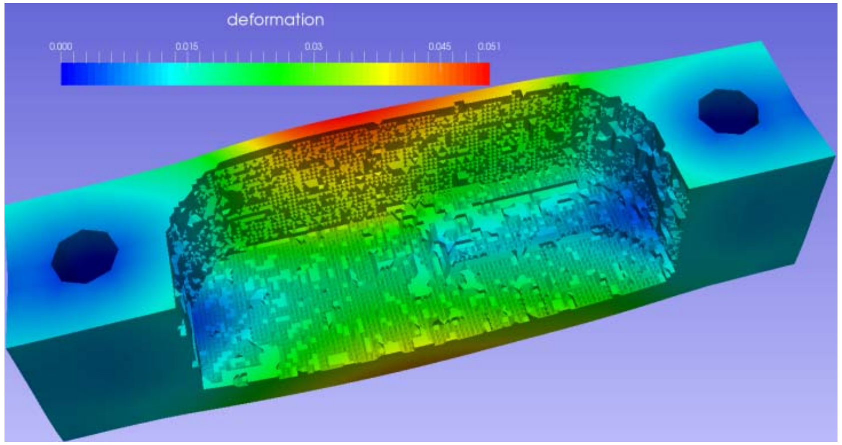


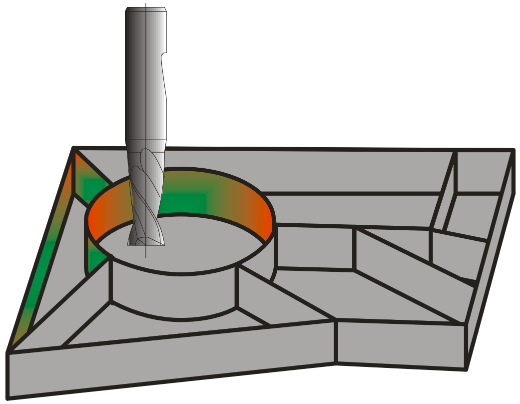
BIAS ID 172200

Joint work with
Andreas Luttmann,
Annika Bohlen and Hannes Freiße (BIAS), Martin Hunkel and Jeremy Epp (IWT)

BMWi/AiF Project “MUSA – Characterization and Modelling of repeated phase transitions in tool steels during additive processes”

Application 3:
Distortion in milling processes





Joint work with
Carsten Niebuhr, **Jost Vehmeyer, Iwona Piotrowska,** and **Peter Maaß**
Berend Denkena and **Daniel Niederwestberg** (IFW Hannover)
Jonathan Montalvo-Urquizo and **Maria G Villarreal-Marroquin**
(CIMAT / Modeling Optimization and Computing Technology SAS de CV, Monterrey, MX)
Project in DFG Priority Program 1480
and DAAD-CONACYT exchange project

Motivation:
Thermal challenges in the production process of structural components

Thermal challenges

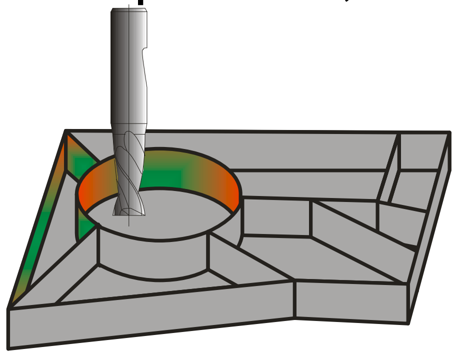
- Significant shape deviation of the workpiece
- Shape errors especially between clamping elements
- Various clamping elements are needed

Final goal

Reduction of shape deviation by simulation and compensation of thermal effects

Milling/drilling of metal workpieces

Cutting process induces heating of workpiece,
Thermal expansions produce deformation of workpiece under process,
without correction, cutter removes material incorrectly

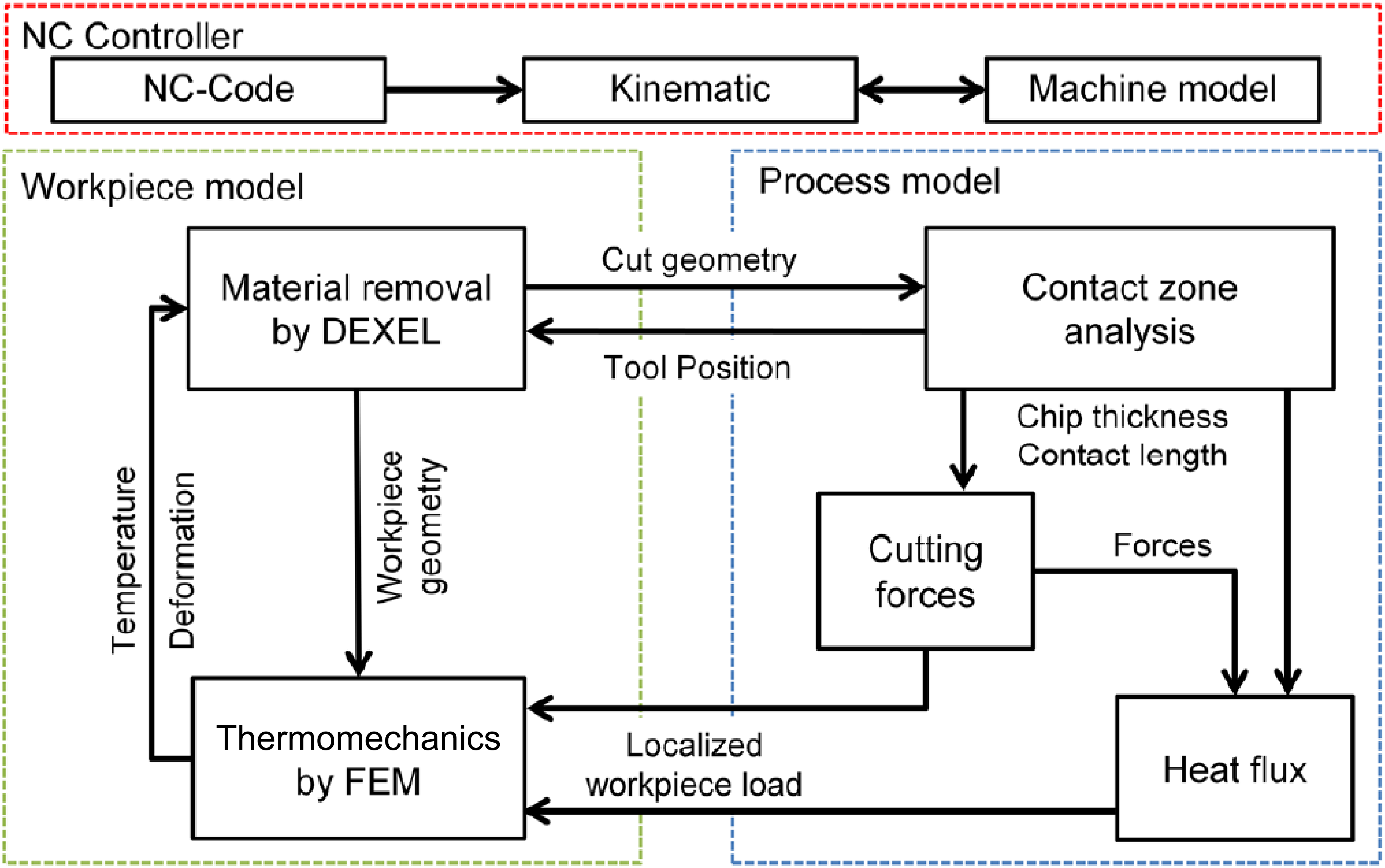


Thermomechanical model for cutting process

Heat and forces are produced by cutting tool.
Process model: based on tool shape and velocity, chip thickness, …
Chip thickness depends on tool and workpiece positions
Here, thermomechanical deformation of workpiece enters!

Tool path is adjustable / controllable!

Detailed modelling and simulation approach



Process model: Cutting Tool

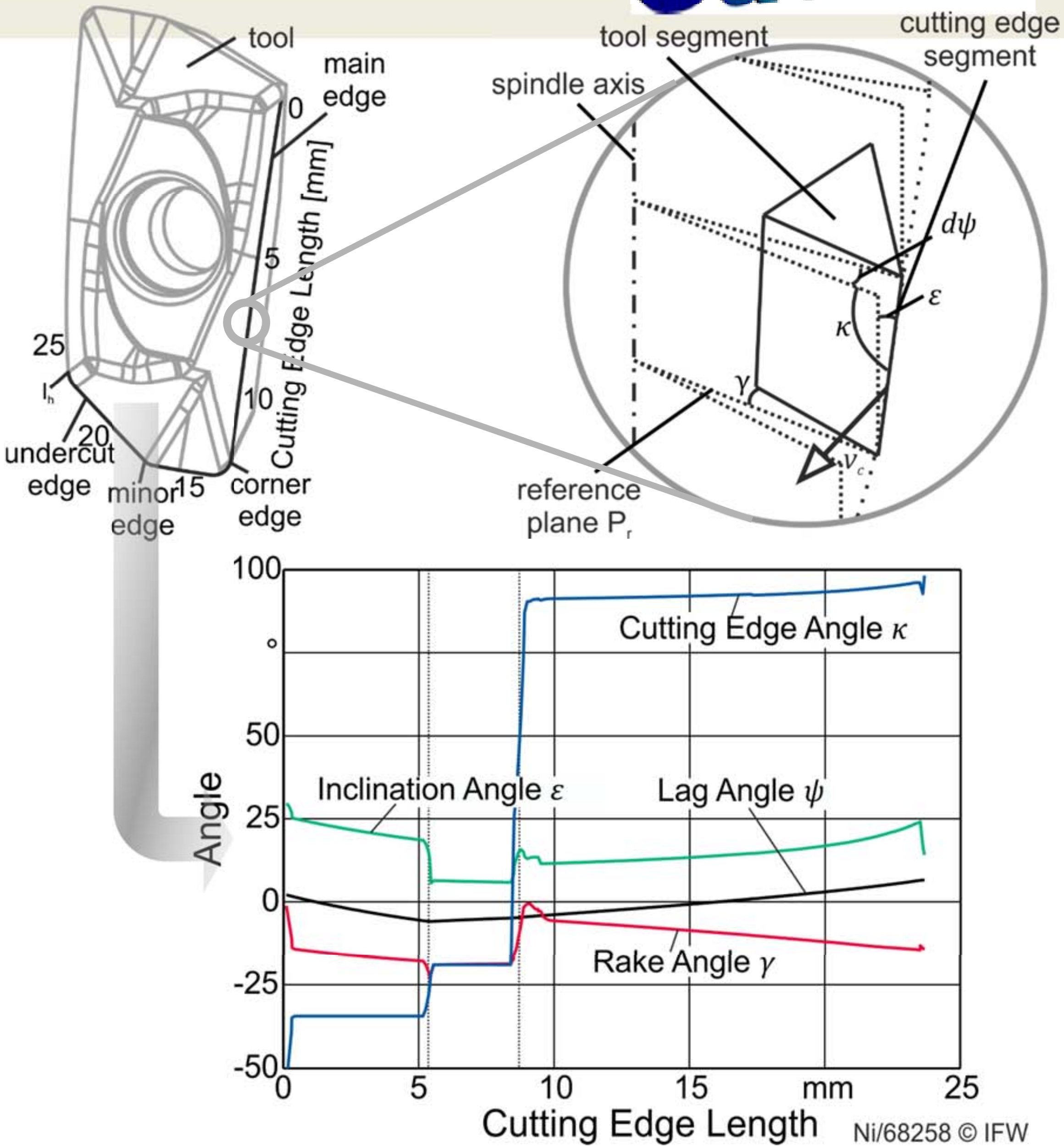
CutSim

Aim

General method for contact zone analysis

Procedure

- Discretization of detail tool model along the cutting edge
- Analysis of tool model for the discrete parts of the cutting edge
- Determination of local tool characteristics, like coordinate transformation $R(s,t)$
- Generation of tool model by rotation of the cutting edge segments
- Assignment of tool characteristics to the body of revolution



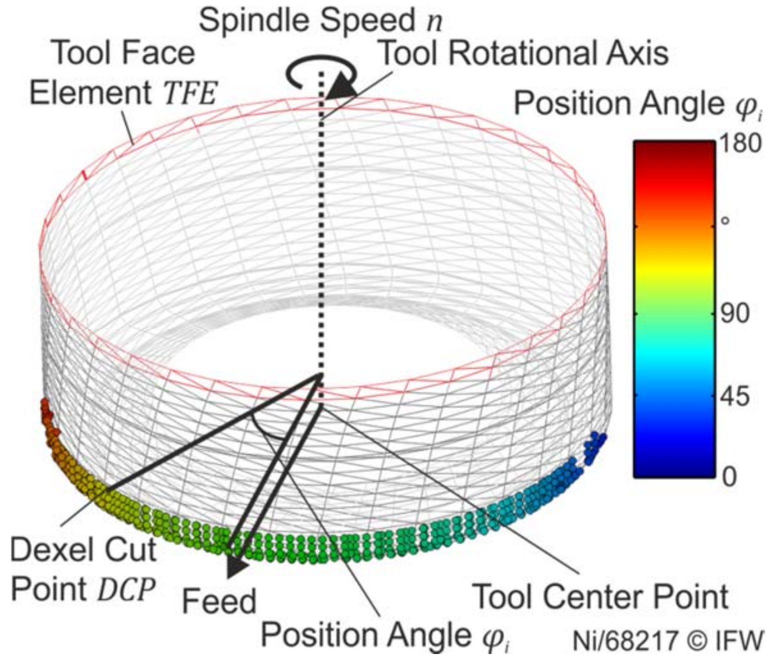
Process model: Forces and heat source

Aim

Determination of the localized thermal and mechanical workpiece load

Procedure

- Assignment of dexel cut points (*DCP*) on the tool model
- Mapping the *DCP*s on the discrete tool face elements (*TFE*)
- Approximation of position angle φ_i for every *DCP*
- Forces are directly measurable
- Calculation of heat flux as result of cutting forces and an empirical slitting function $N(v_c, t)$
- Transfer results to the workpiece



$$\varphi_i = \sphericalangle\left(\overrightarrow{v_{f,TFE}}, \overrightarrow{DCP}\right) - 90°$$

$$h = h_{ideal} \cdot \frac{\cos(\kappa - \alpha)}{\cos(\gamma)} \quad \text{with} \quad h_{ideal} = f_z \cdot \sin(\varphi_i)$$

$$F_c(t) = \int_0^{l_h} R(s,t)\,dF(K,s,t)\,ds$$

$$\dot{Q}(t) = F_c(t) \cdot v_c \cdot N(v_c, h)$$

Workpiece model: Thermomechanical model, FEM

Simulation of thermomechanics of the workpiece

Coupled finite element & dexel models

FEM model for temperature θ

$$\begin{aligned} \rho c_e \theta_t - div(\kappa \nabla \theta) &= 0 && \text{in } \Omega_s(t) \times [0,\mathrm{T}], t \geq 0 \\ -\kappa \nabla\theta \cdot \mathbf{n} &= q(t,x) && \text{on } \Gamma_N(t) \times [0,\mathrm{T}] \end{aligned}$$

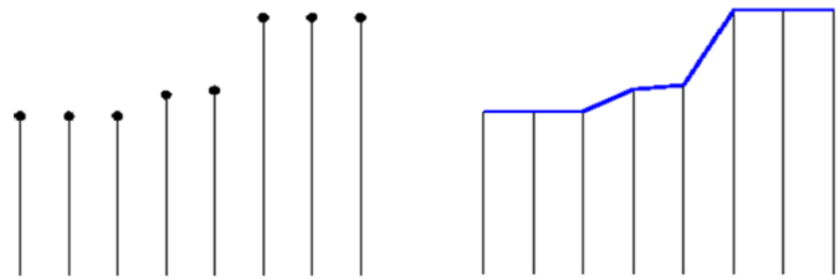
and deformation $\boldsymbol{u}$

$$\begin{aligned} -\mu \Delta \boldsymbol{u} - (\mu + \lambda)\text{grad div } \boldsymbol{u} &= \boldsymbol{f} && \text{in } \Omega_s(t), t \geq 0 \\ \boldsymbol{u} &= 0 && \text{on } \Gamma_D(t) \\ -\left(\lambda tr\big(\epsilon(\boldsymbol{u})\big)I + 2\mu\epsilon(\boldsymbol{u})\right) \cdot \mathbf{n} &= \boldsymbol{g}(x,t) && \text{on } \Gamma_N(t) \end{aligned}$$

in time dependent subdomain $\Omega_s(t)$
with moving boundary $\Gamma_N(t)$

Discrete domain

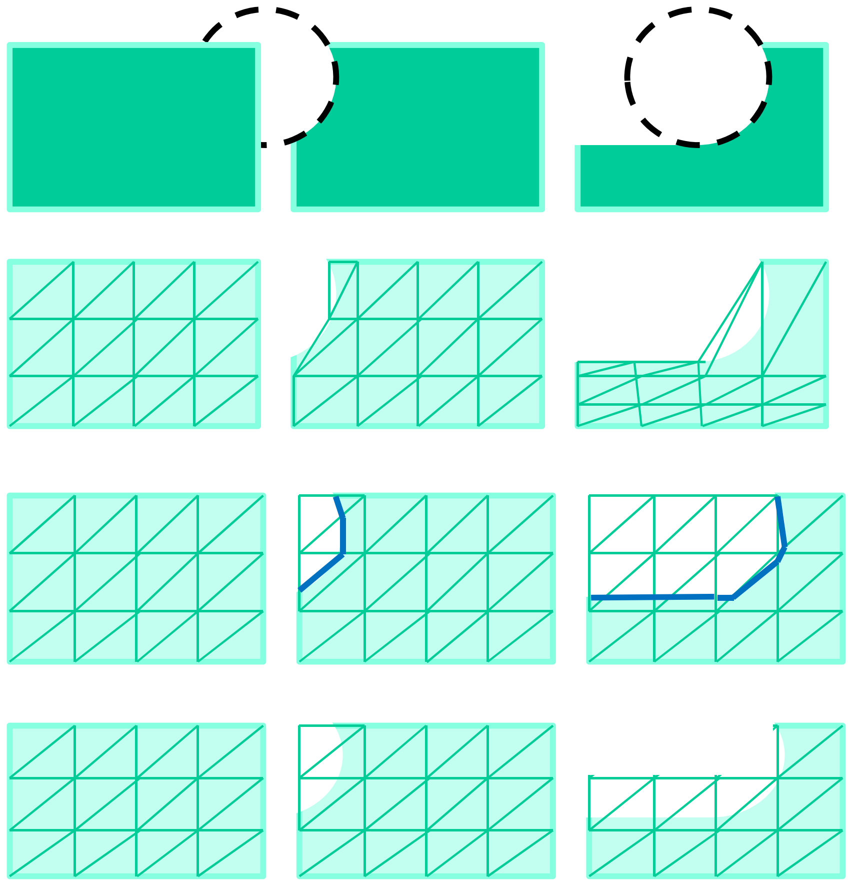
given by material removal
via dexel model



Dexel **Graph**

Approximation of domain

Approximation of time dependent subdomain $\Omega_s(t)$ with moving boundary $\Gamma_N(t)$



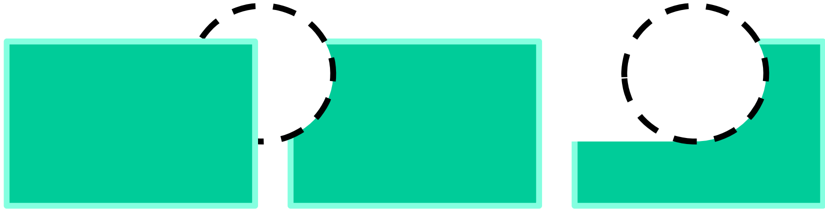
Several possiblities:

- Moving mesh (ALE approach)
- Remeshing at every time step
- XFEM / Cut Cells on a fixed mesh
- Subset of a fixed (locally refined) mesh

Meshes should later be efficiently usable for an optimization procedure

Approximation of domain

Approximation of time dependent subdomain $\Omega_s(t)$ with moving boundary $\Gamma_N(t)$



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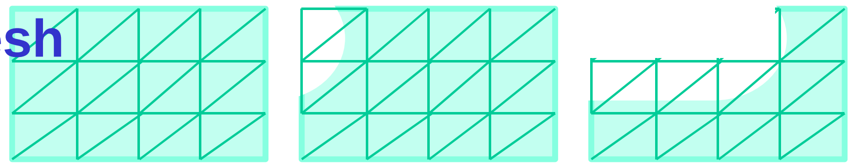


Meshes should later be efficiently usable for an optimization procedure

Workpiece model: Thermomechanical model, FEM

Zentrum für Technomathematik

Simulation of thermomechanics of the workpiece

Coupled finite element & dexel models

FEM model for temperature θ

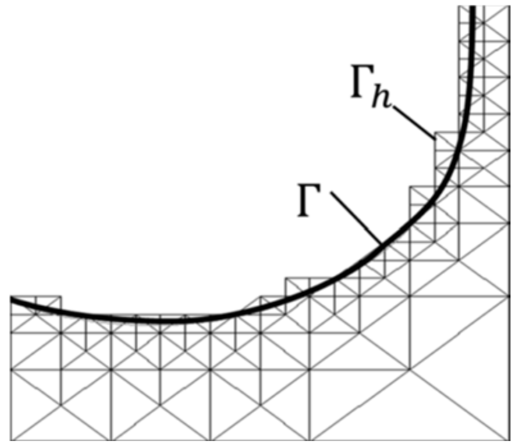
$$\rho c_e \theta_t - div(\kappa \nabla \theta) = 0 \qquad \text{in } \Omega_s(t) \times [0,\mathrm{T}], t \geq 0$$
$$-\kappa \nabla \theta \cdot \mathbf{n} = q(t,x) \qquad \text{on } \Gamma_N(t) \times [0,\mathrm{T}]$$

and deformation $\boldsymbol{u}$

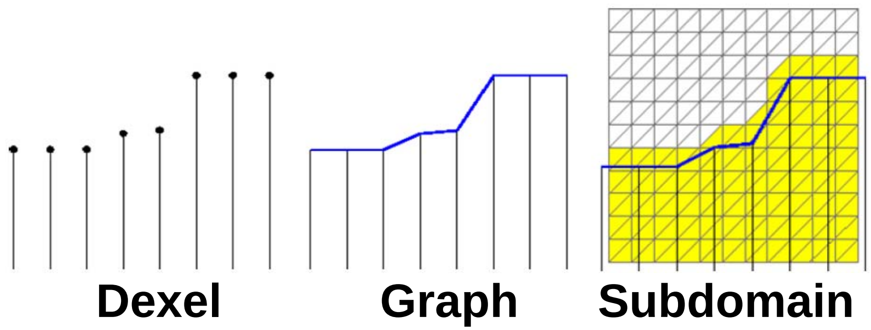
$$-\mu \Delta \boldsymbol{u} - (\mu + \lambda)\operatorname{grad}\operatorname{div}\boldsymbol{u} = \boldsymbol{f} \qquad \text{in } \Omega_s(t), t \geq 0$$
$$\boldsymbol{u} = 0 \qquad \text{on } \Gamma_D(t)$$
$$-\left(\lambda tr\left(\epsilon(\boldsymbol{u})\right)I + 2\mu\epsilon(\boldsymbol{u})\right) \cdot \mathbf{n} = \boldsymbol{g}(x,t) \qquad \text{on } \Gamma_N(t)$$

in time dependent subdomain $\Omega_s(t)$
with moving boundary $\Gamma_N(t)$

Discrete subdomain $\Omega_{s,h}(t)$ given by subset of FEM mesh elements



Subset given by material removal via dexel model



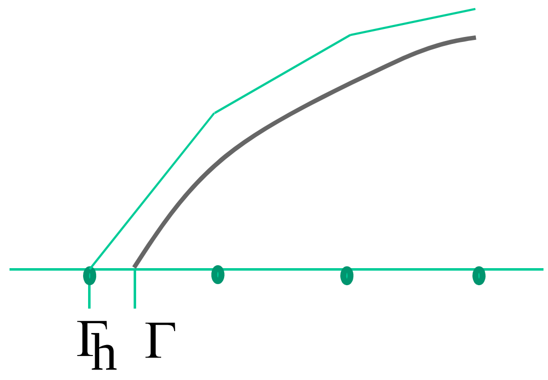
Approximation of domain
Boundary conditions

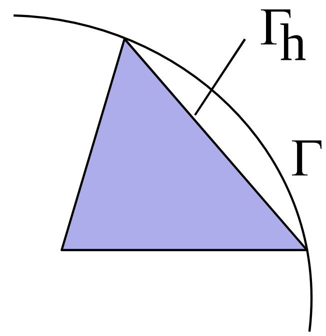
Approximation of time dependent subdomain $\Omega_s(t)$ with moving boundary $\Gamma_N(t)$

Quality of approximation?

Look at an **elliptic problem**

For the **Dirichlet** problem**,** it is well known that you get P^1 optimal order only when you approximate a curved boundary of **order h^2** (by interpolation, e.g.).

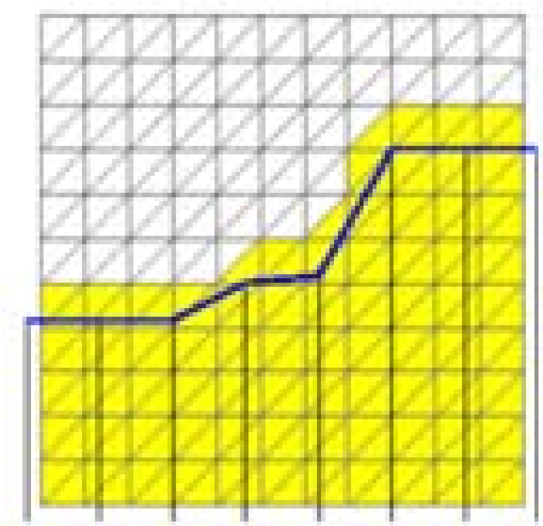




With **Neumann** boundary data, you might expect to get a better approximation in some cases, but this is not true in general (look at travelling wave solution for heat equation)

Approximation of domain

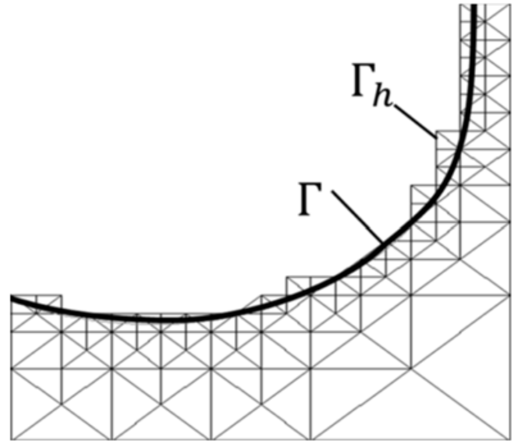
Approximation of time dependent subdomain $\Omega_s(t)$ with moving boundary $\Gamma_N(t)$



Nevertheless, we use a discrete domain

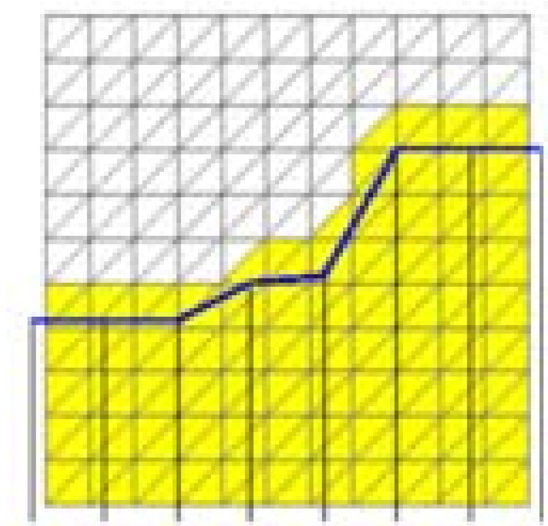
$$\Omega_h(t) := \{T \in \mathcal{T}_h : T \cap \Omega(t) \neq \emptyset\}$$
$$\Gamma_h = \partial\Omega_h$$

Approximation can be improved by local mesh refinement near the boundary.



Approximation of domain

Approximation of time dependent subdomain $\Omega_s(t)$ with moving boundary $\Gamma_N(t)$



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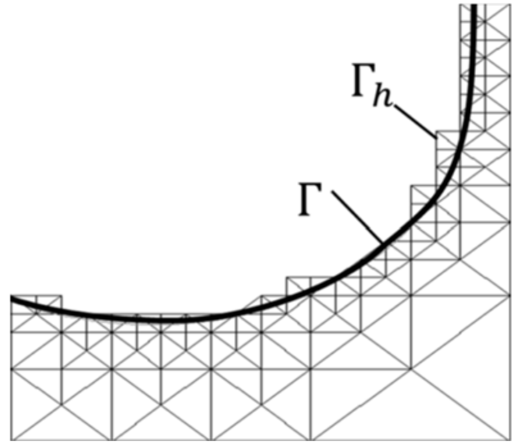


Continuous problem:

$$(\nabla u, \nabla v)_\Omega = Q(v) := \int_\Gamma qv\, do \quad \forall v \in X$$

Discrete problem:

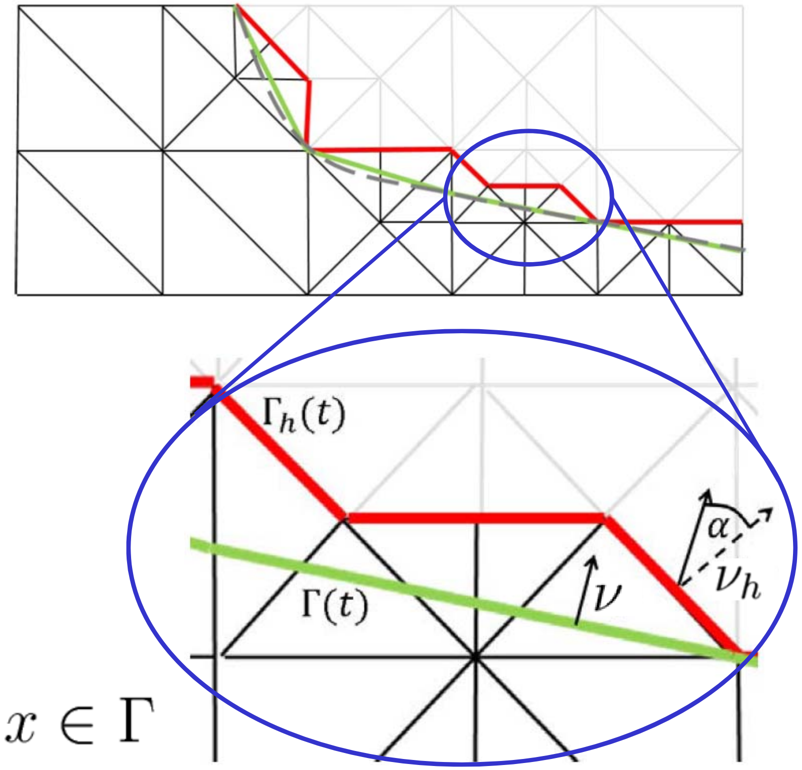
$$(\nabla u_h, \nabla v_h)_{\Omega_h} = Q_h(v_h) := \ ? \qquad \forall v_h \in X_h$$

Approximation of time dependent subdomain $\Omega_s(t)$ with moving boundary $\Gamma_N(t)$

Neumann boundary data: on RHS of weak formulation,

replace $$\int_\Gamma q(x)v(x)dx$$

by $$\int_{\Gamma_h} q_h(x)v_h(x)dx$$



with suitable modification of flux density,

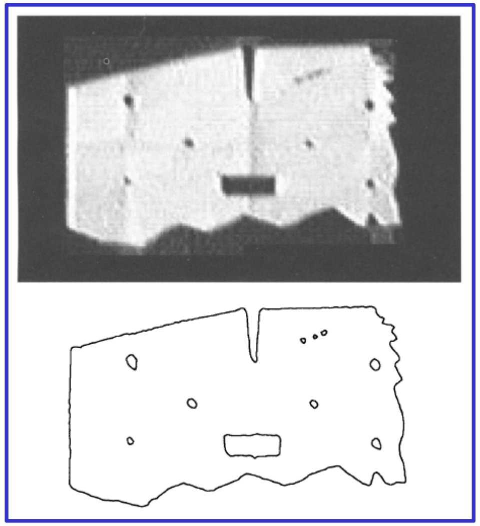
accounting for different length, etc.

so that amount of total flux is unchanged

Simple idea: use

$$q_h(x_h) := q(x)(\nu(x)\cdot\nu_h(x_h)) \quad x_h \in \Gamma_h,\, x \in \Gamma$$

Approximation of domain
Boundary conditions



Ivo Babuška & Jan Chleboun [Math.Comp. 2001]
propose a more general approach for
Neumann boundary data on domains with “uncertanties”:
Idea: choose a vector valued function around $\partial\Omega$

$$\bar{Q} \in H_0^1(B)^d \quad \textbf{with} \quad \bar{Q}\cdot\nu = q \quad \textbf{on} \quad \partial\Omega$$

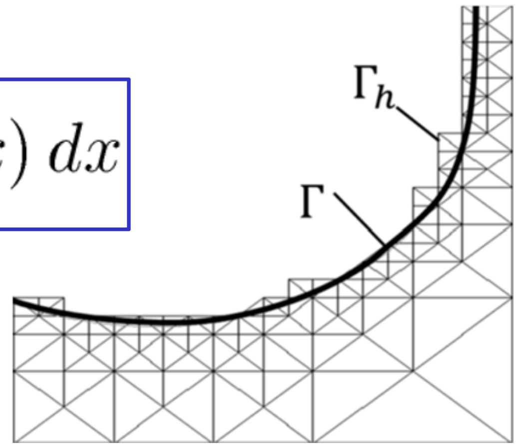
and replace

$$\int_{\partial\Omega} q(x)v(x)dx$$

by

$$\boxed{\int_{\partial\Omega} v(x)\, d\bar{Q} := \int_{\Omega} \bar{Q}\cdot\nabla v(x) + \operatorname{div}\bar{Q}(x)\, v(x)\, dx}$$

This can be used also for the discrete domain,



$$\boxed{Q_h(v) := \int_{\partial\Omega_h} v(x)\, d\bar{Q}}$$

Convergence of solutions and estimates were shown by Babuška&Chleboun.

Approximation of domain
Error analysis

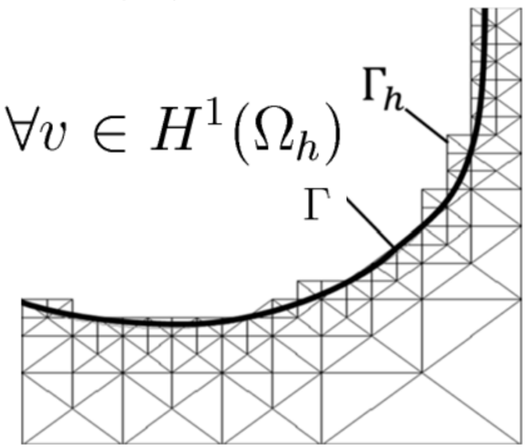
Ivo Babuška & Jan Chleboun [Math.Comp. 2001]
prove estimates like

$$\boxed{\|u-\tilde{u}_h\|_\Omega^2 \le h_\Gamma C(|\bar{Q}|_{H^1(\Omega_h)}, |\bar{Q}|_{H^2(\Omega_h)}, \|\nabla \bar{Q}\|_{L^\infty(\Omega_h\setminus\Omega)})}$$

where u , $\tilde{u}_h$ are the continuous solutions of the problems

$$u \in H^1(\Omega): \quad \int_\Omega A\nabla u \nabla v + uv\, dx = Q(v) \quad \forall v \in H^1(\Omega)$$

$$\tilde{u}_h \in H^1(\Omega_h): \quad \int_{\Omega_h} A\nabla \tilde{u}_h \nabla v + \tilde{u}_h v\, dx = Q_h(v) \quad \forall v \in H^1(\Omega_h)$$



for Lipschitz domains $\Omega \subset \Omega_h \subset I\!R^2$

and h_Γ is the distance between Γ and Γ_h

Approximation of domain
Error analysis

The error

$$\|u - u_h\|_\Omega$$

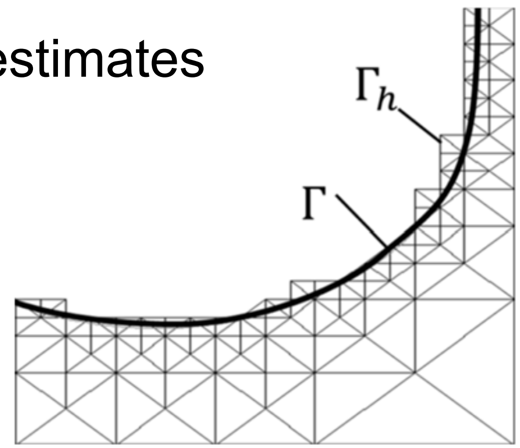
can be split into

$$\|u - u_h\|_\Omega \leq \|u - \tilde{u}_h\|_\Omega + \|\tilde{u}_h - u_h\|_{\Omega_h}$$

the first term can be estimated via B&C (a-priori)
the second term using standard a-priori and a-posteriori estimates

To do: a-posteriori estimate for the first term

Nevertheless, a mesh refinement at the boundary
and an adaptive refinement in the domain
should give good results.



Approximation of domain

Use same idea for

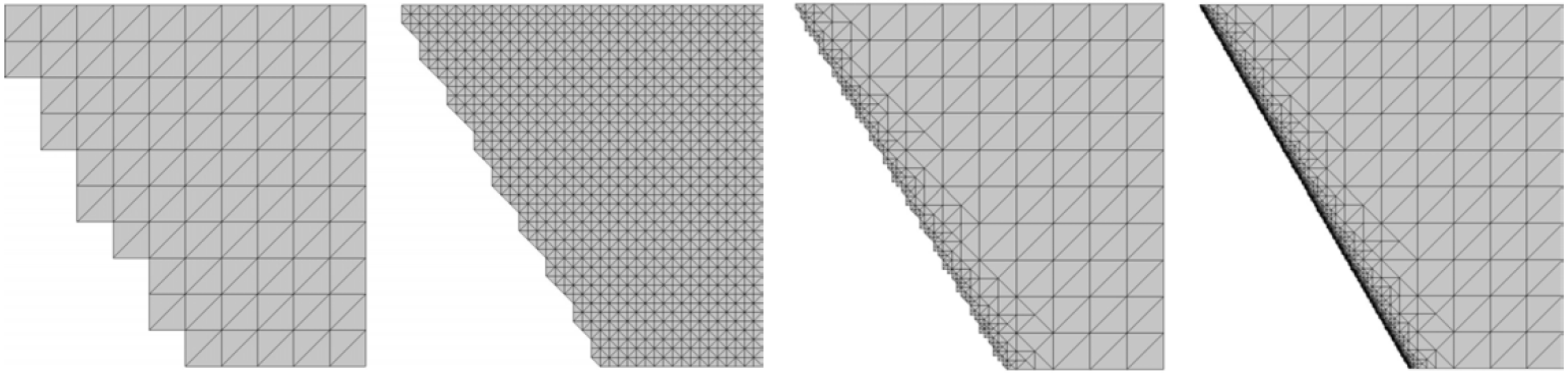
(quasi-stationary) thermo-mechanics
with boundary forces on $\Gamma(t)$

time dependent **heat equation** on time-varying domain

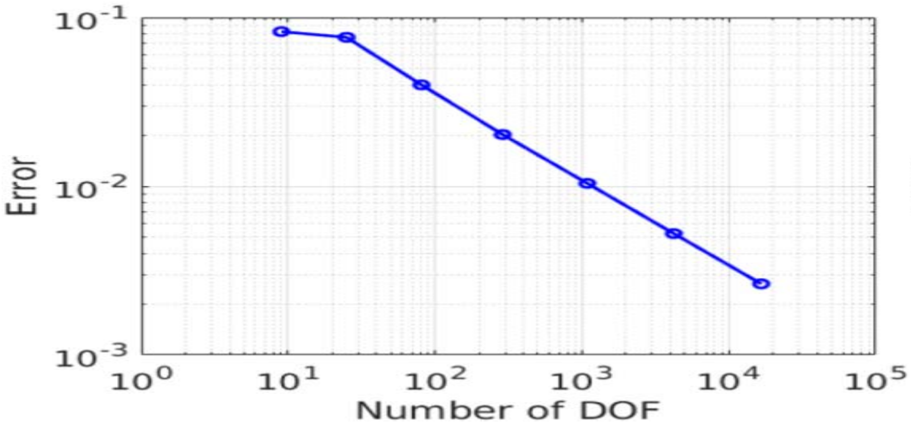
Approximation of domain
Numerical experiments

Numerical experiments [Carsten Niebuhr]:

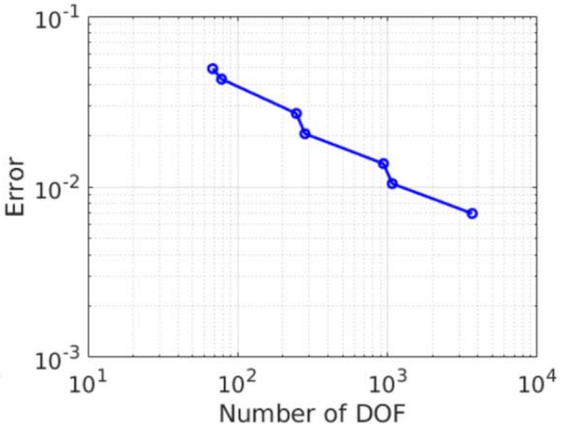
Known exact solution (travelling wave, exponential)



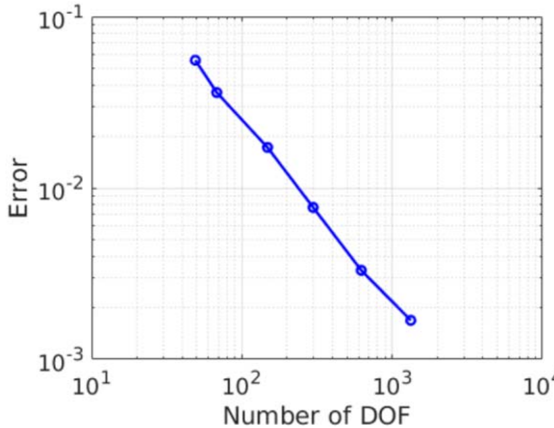
Global and adaptive local refinements -- L∞(L²) error



Global refinement



Adaptive with standard indicators

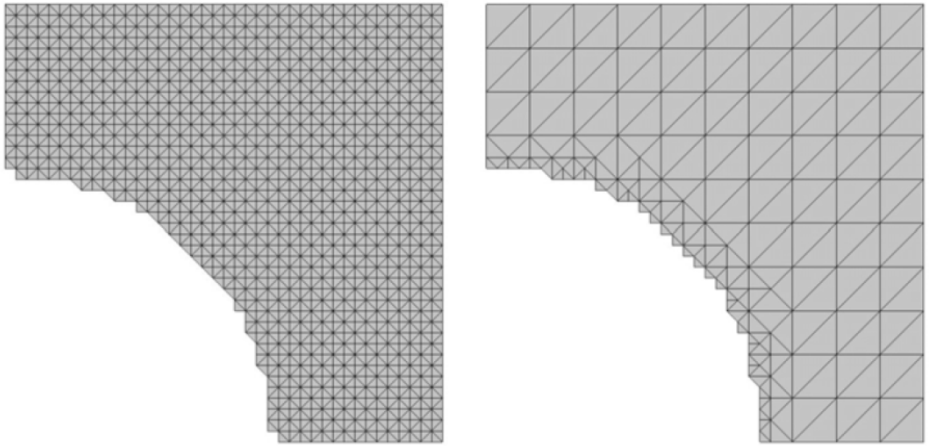


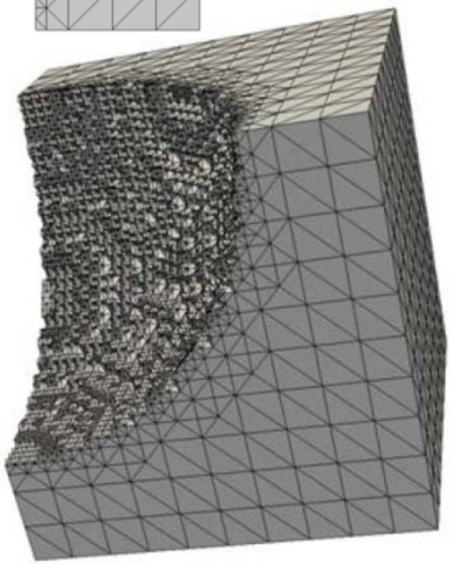
Adaptive with special indicators

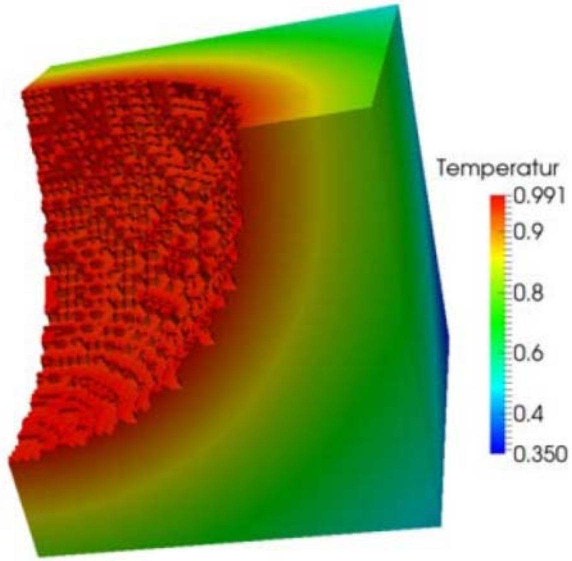
Approximation of domain
Numerical experiments

Numerical experiments [Carsten Niebuhr]:

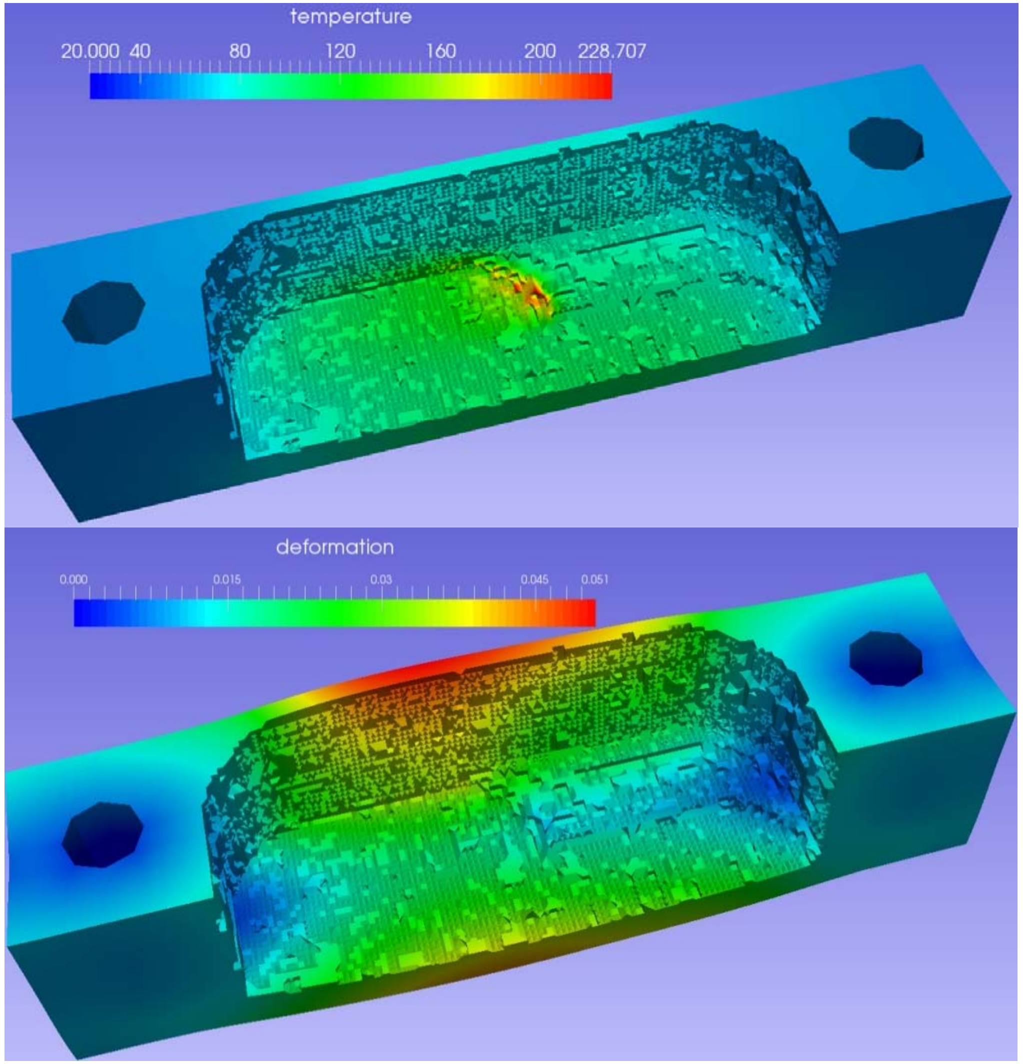
Known exact solution (travelling wave, exponential)







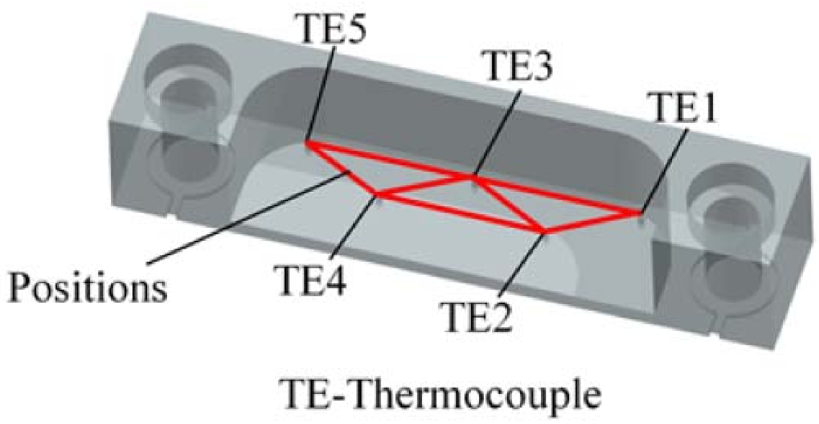
Workpiece model: Thermomechanical model, FEM

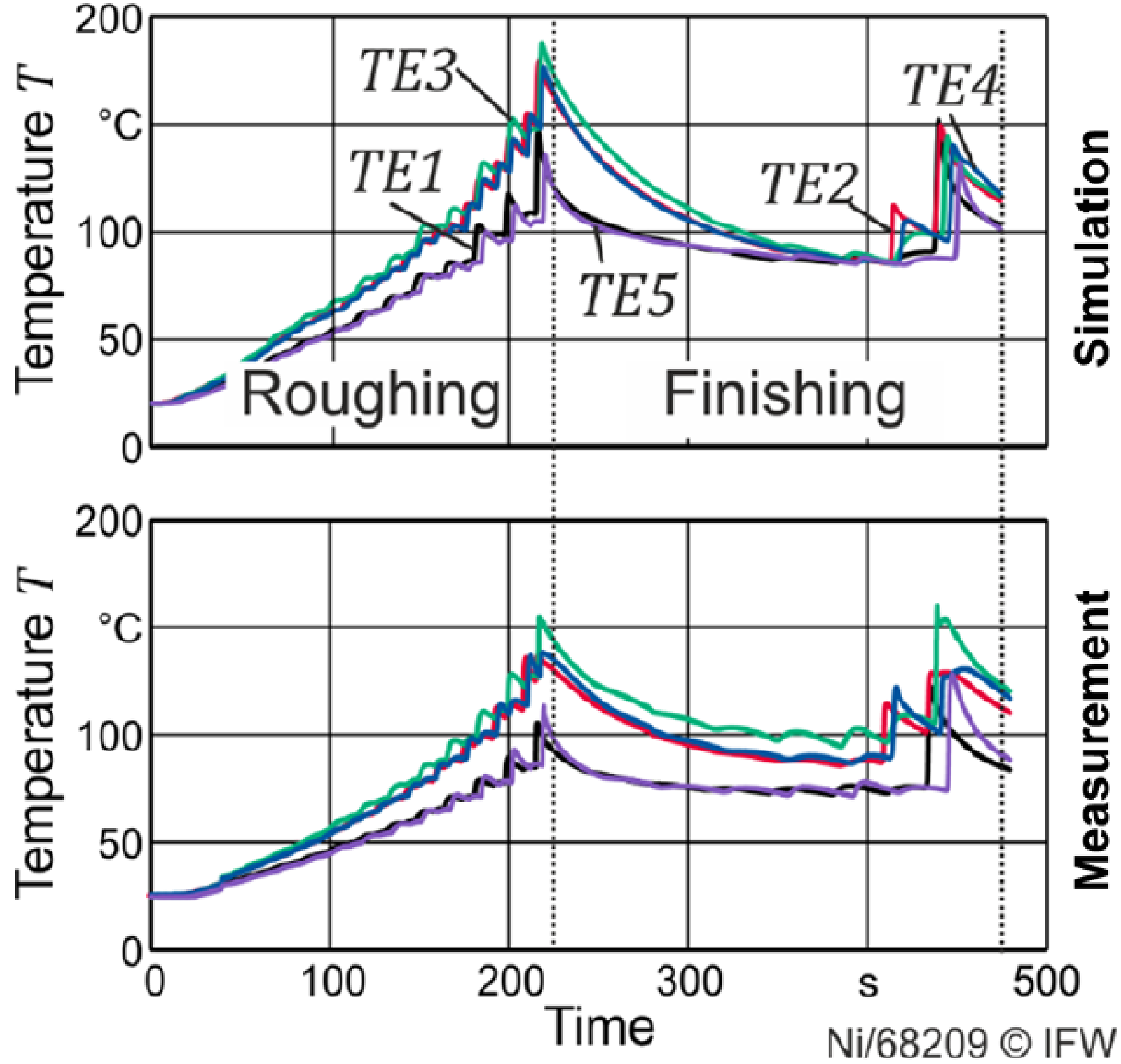


Visualization of temperature and deformation
on time dependent domain by FEM

Video

Validation: temperature





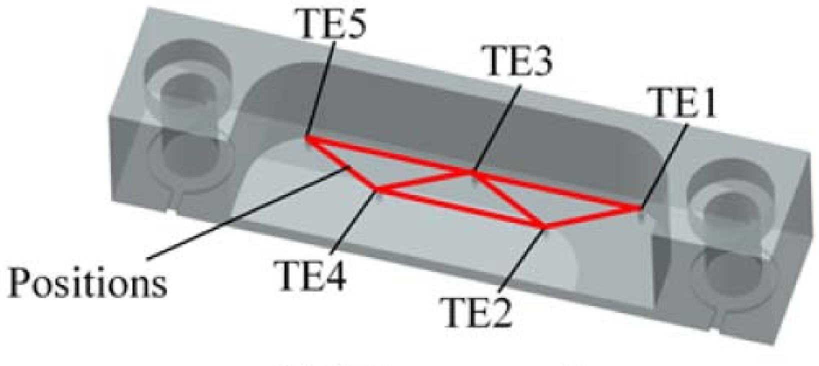
Process:
- f_z = 0,05 - 0,15 mm/z
- v_c = 275 m/min
- Dry Milling

Maschine Tool:
- Manufacturer: HELLER
- Type: MCi16

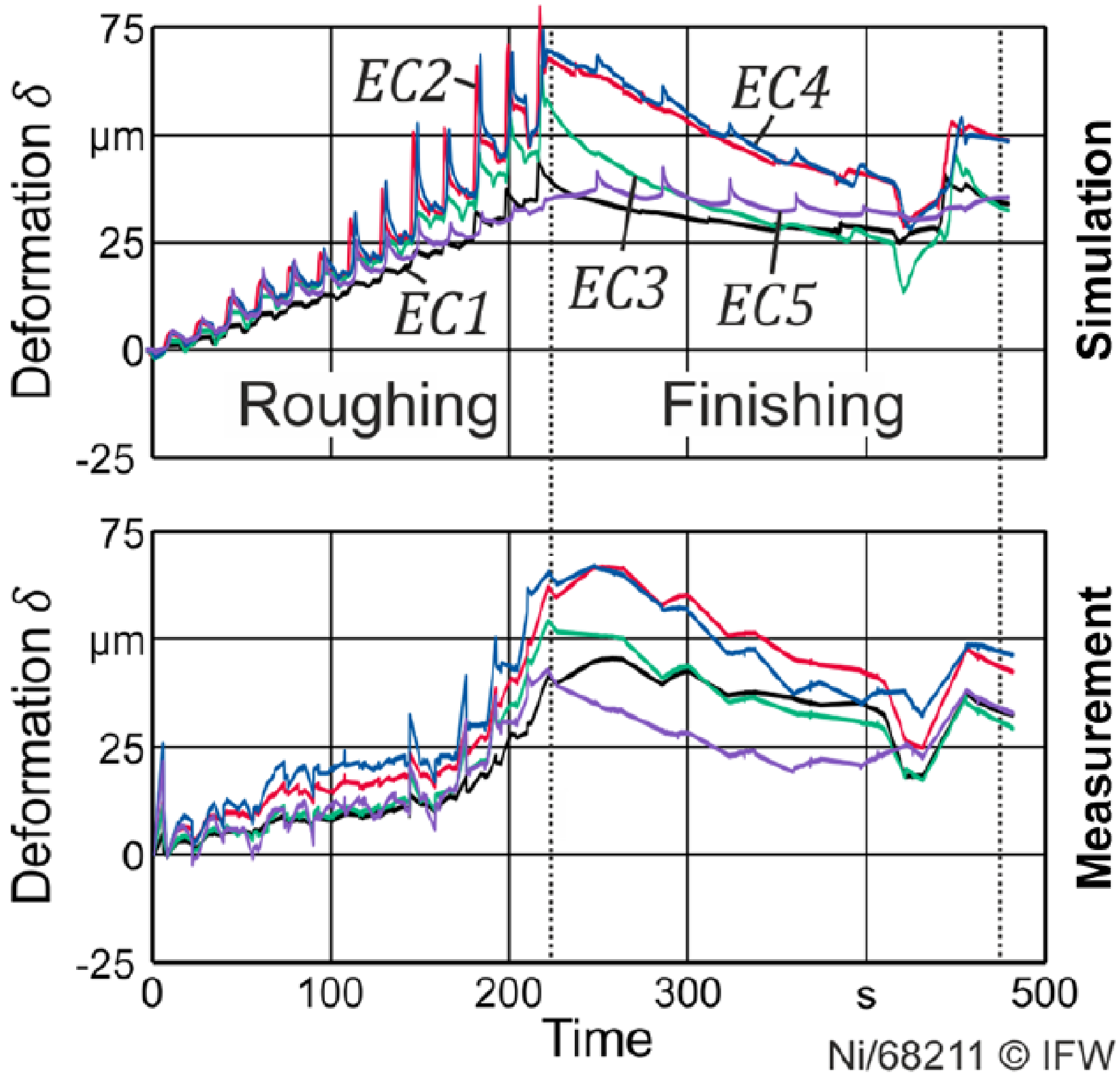
Messurement:
- Thermocouples: Typ K (NiCr-Ni)
- Amplifier: SAK12-461-100-10

Material:
- C45EN

Validation: deformation



TE-Thermocouple



Ni/68211 © IFW

Process:

- f_z = 0,05 - 0,15 mm/z
- v_c = 275 m/min
- Dry Milling

Maschine Tool:

- Manufacturer: HELLER
- Type: MCi16

Messurement:

- Thermocouples: Typ K (NiCr-Ni)
- Amplifier: SAK12-461-100-10

Material:

- C45EN

Optimization of milling processes

Goals: speed of process, quality of final geometry (deviation from prescribed)

Optimal control problem:

Control u: variation of cutting process (tool path, rotational speed, …)

State $(\theta, \mathbf{v}, \Omega)$: temperature, deformation, and time dependent domain

$$\begin{pmatrix} \dot{\theta}(t) \\ 0 \end{pmatrix} + \begin{pmatrix} A(t) & 0 \\ 0 & S(t) \end{pmatrix} \begin{pmatrix} \theta(t) \\ \mathbf{v}(t) \end{pmatrix} = F(\theta(t), \mathbf{v}(t), u(t))$$

Boundary data, heat source q and force g in F, and
$\Omega(t)$ depend on cutting process (control u) and deformation $\mathbf{v}$

Here, $\Omega(t)$ is reference domain, decreasing by material removal

Optimal control problem:

Goals: speed of process, quality of final geometry (deviation from prescribed)

Control u: variation of cutting process (tool path, rotational speed, …)

State $(\theta,\mathbf{v},\Omega)$: temperature, deformation, and time dependent domain

$$\begin{aligned} \dot{\theta} - \nabla\cdot(\kappa\nabla\theta) &= 0 && \text{in } \Omega(t) \\ \kappa\nabla\theta\cdot\mathbf{n} &= \underline{q_\Gamma(u,\theta,\mathbf{v})} + r(\theta_{ext}-\theta) && \text{on } \partial\Omega(t) \end{aligned}$$

parabolic

$$\begin{aligned} -\nabla\cdot\sigma &= f_v(\theta) && \\ \sigma &= 2\mu D\mathbf{v} + \lambda tr(D\mathbf{v})\mathbb{I} && \text{in } \Omega(t) \\ \mathbf{v} &= 0 && \text{on } \Gamma_D \\ \sigma\mathbf{n} &= \underline{g_\Gamma(u,\theta,\mathbf{v})} && \text{on } \partial\Omega(t)\setminus\Gamma_D \end{aligned}$$

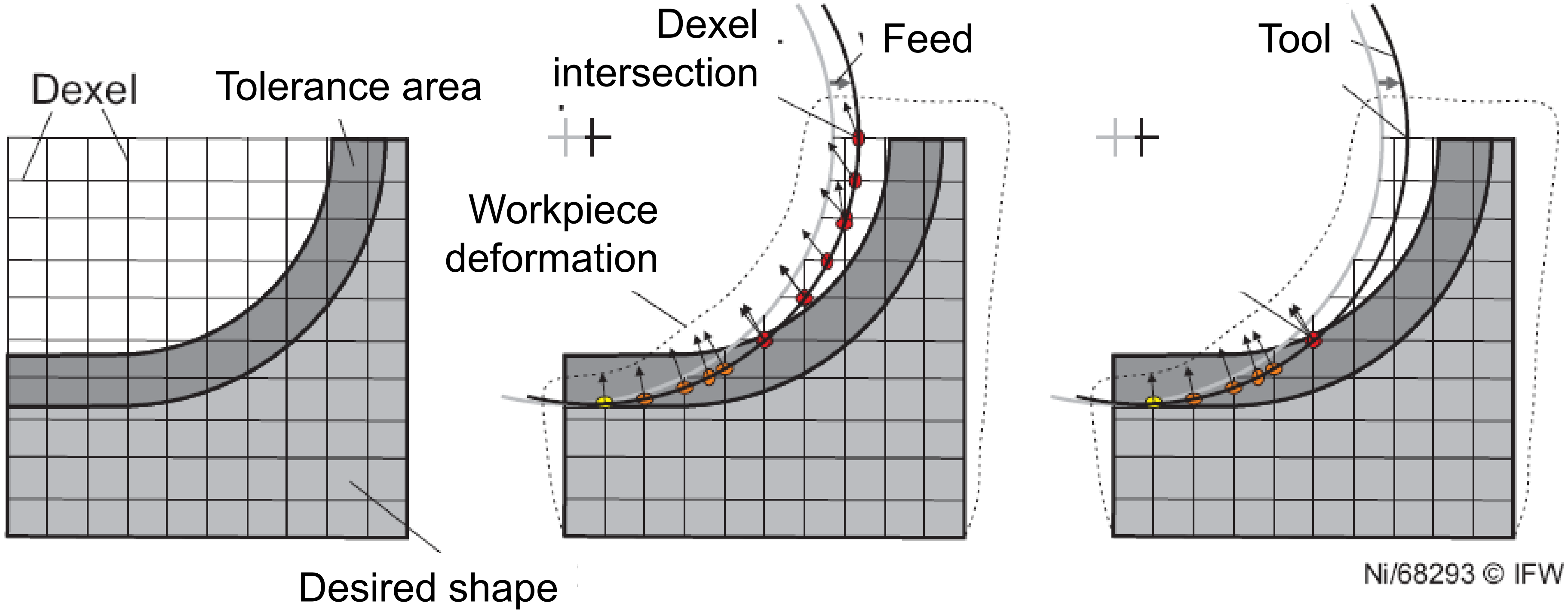
elliptic

$\Omega(t)$ depends on cutting process (control u) and deformation $\mathbf{v}$

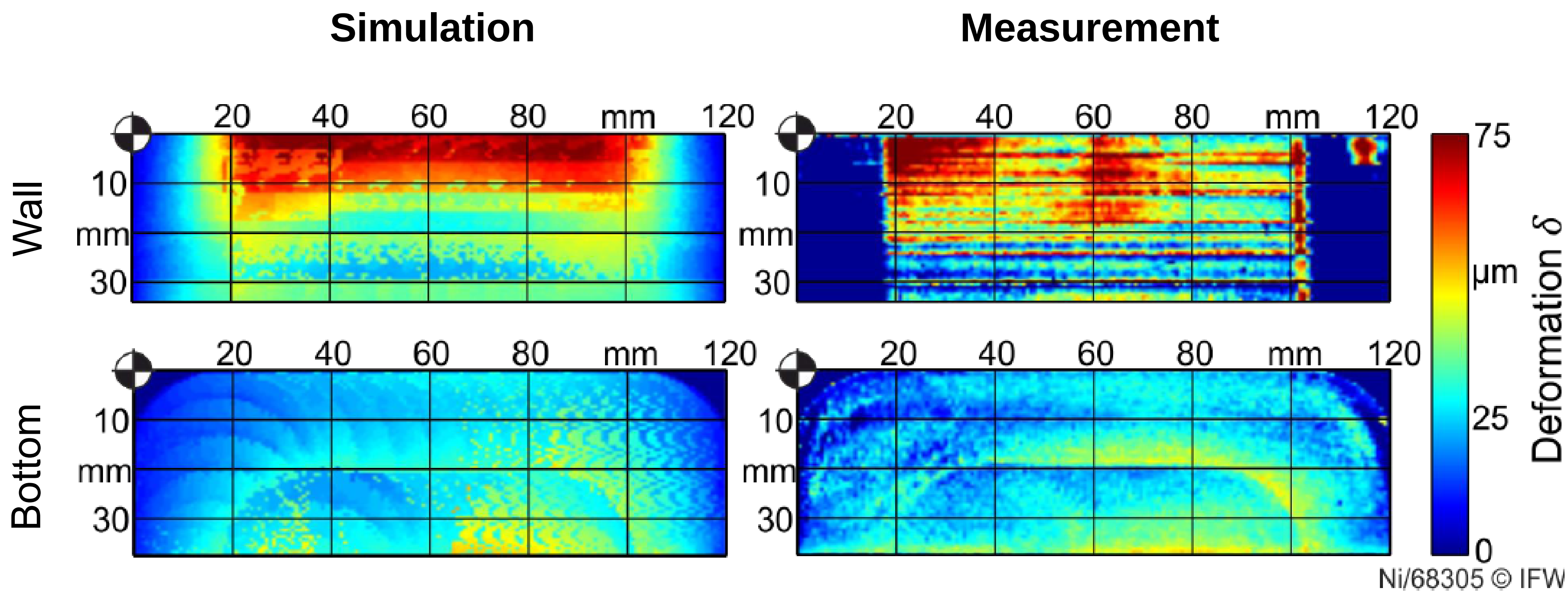
Compensation of distortions

Engineering approach: [Daniel Niederwestberg, PhD thesis 2016]

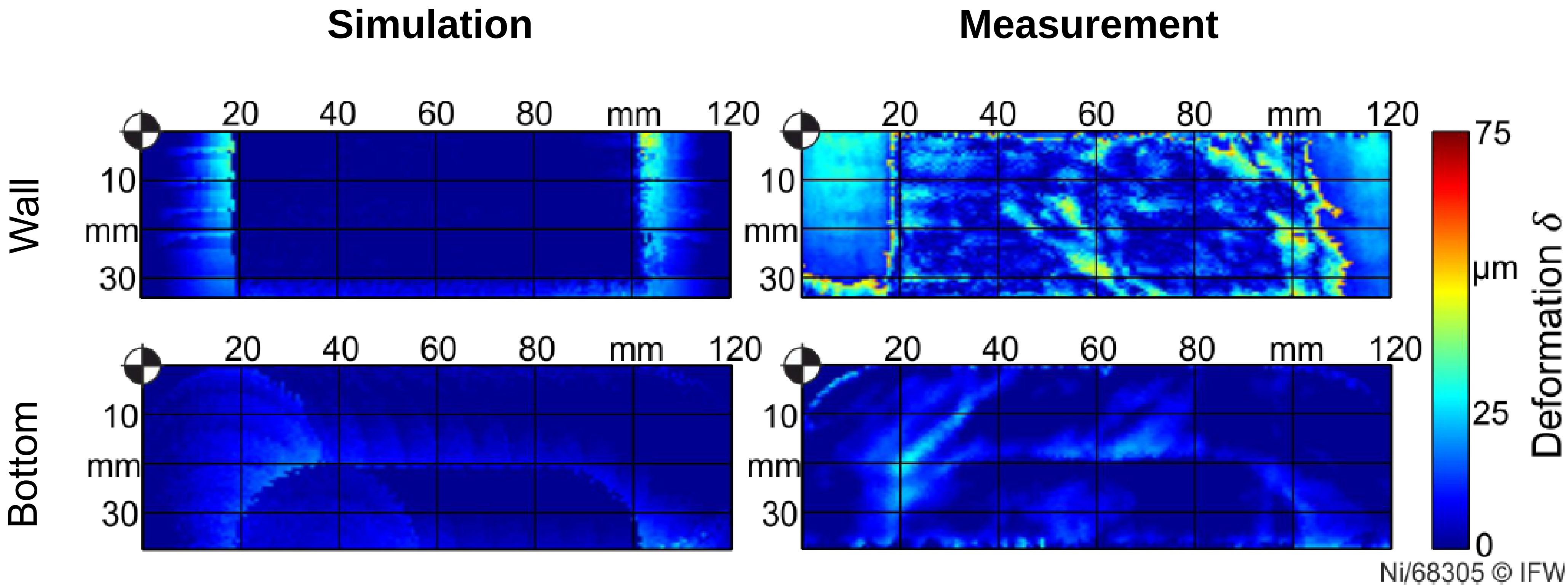
- Error prediction inside the process model
- Compensation by local variation of tool engagement by inverse deformation



Without compensation



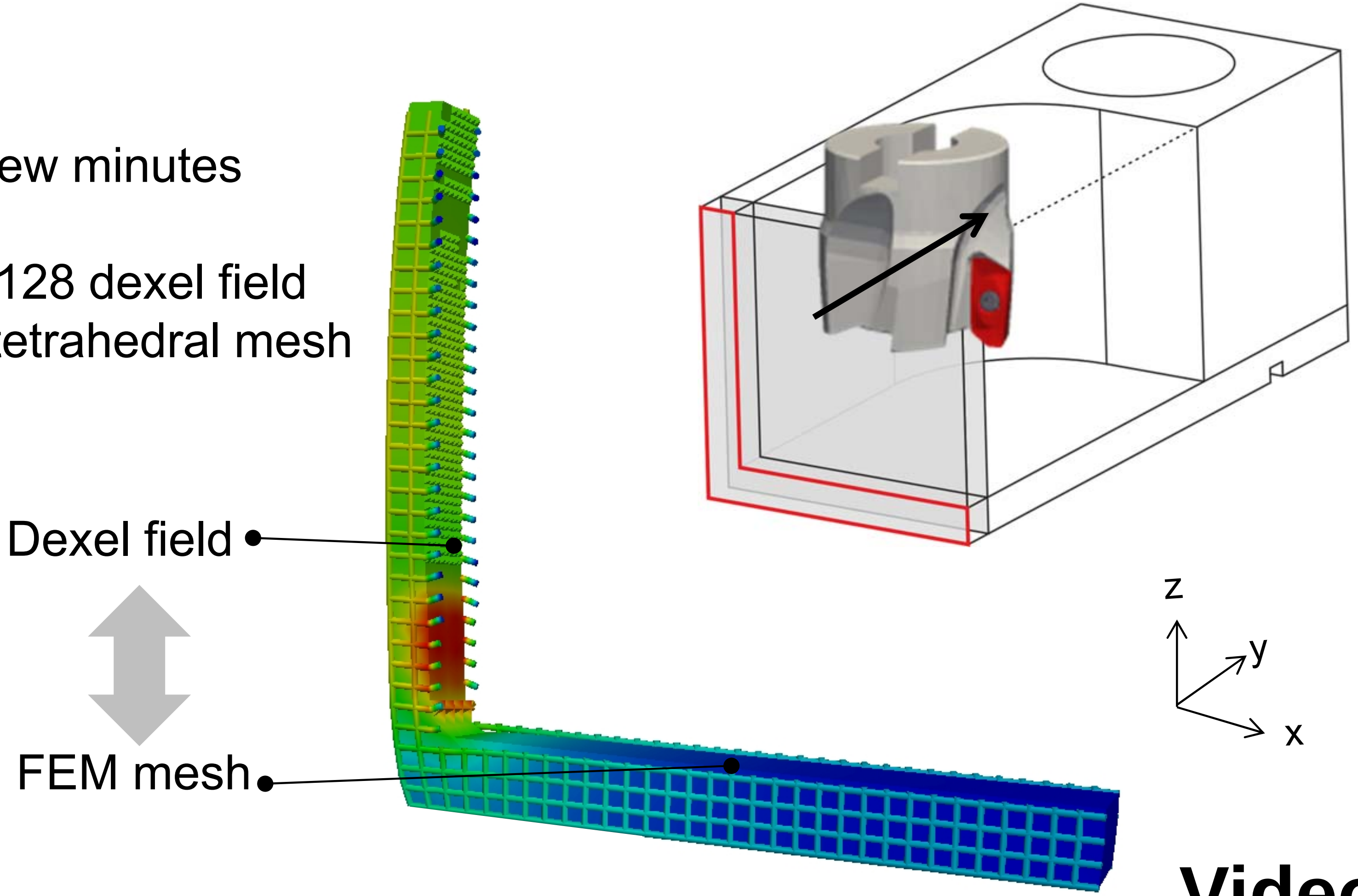
With compensation



Reduction of shape error by 70%

Reduced reference workpiece (L-shape)

– small workpiece
– pseudo 2D
– computing time: a few minutes
– surface model:
    equidistant 128x128 dexel field
– 3D FEM: adaptive tetrahedral mesh



Video

Optimization of process parameters

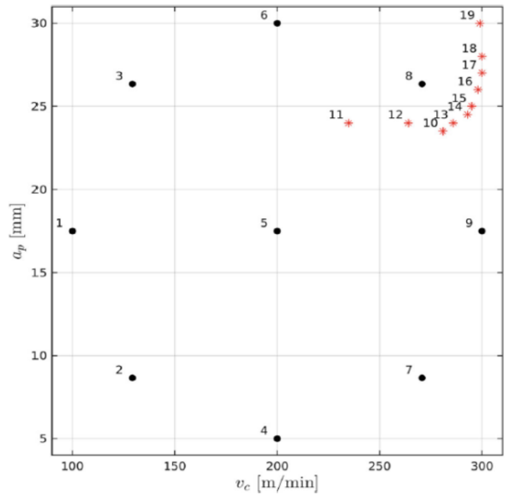
“Full” optimization approach with computation of primal/dual solutions might be possible, but computationally very challenging.

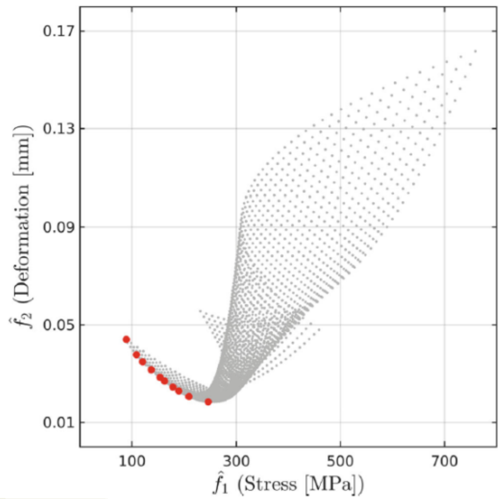
Simpler approach: **“Simulation-based Optimization”**

Replace control-to-error function by a simple approximation computed due to a small number of simulations,

refine the approximation locally (near the optimum)

by adding a few more simulations





Joint work with

Jonathan Montalvo-Urquizo and

Maria G Villarreal-Marroquin

(CIMAT / MOCT, Monterrey, MX)

Optimization of process parameters: Simulation-based Optimization

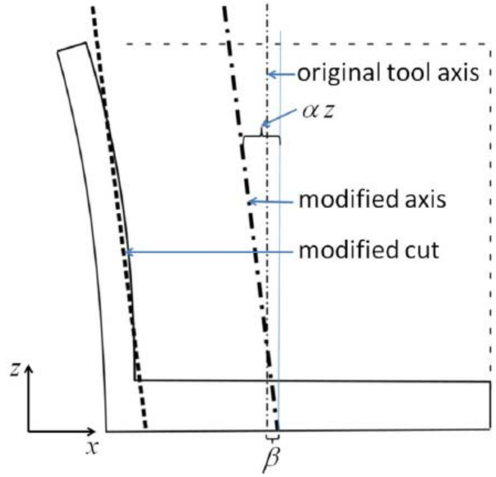
“Simulation-based Optimization”

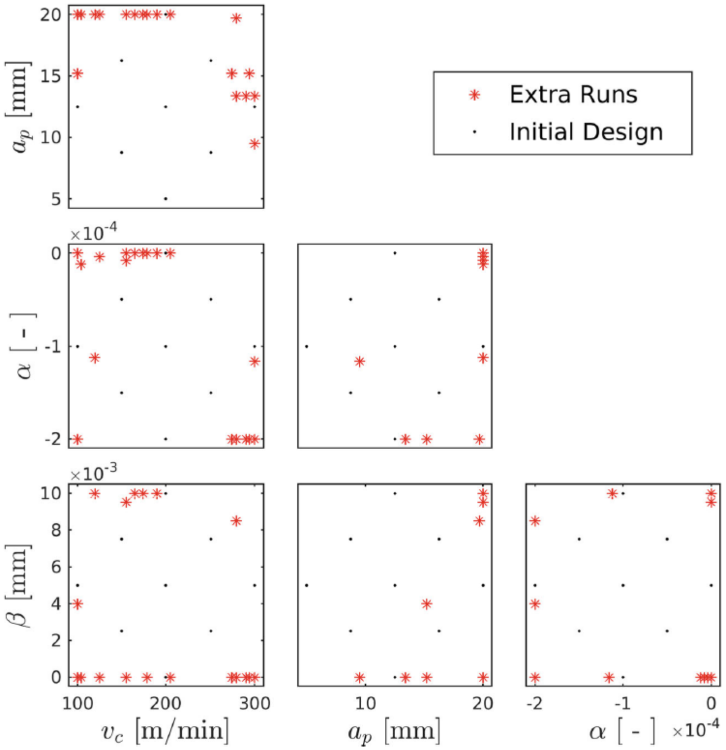
Control: **Tool path variation**

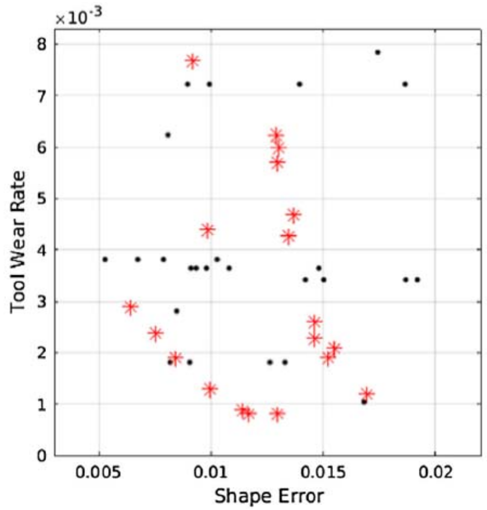
and other cutting parameters

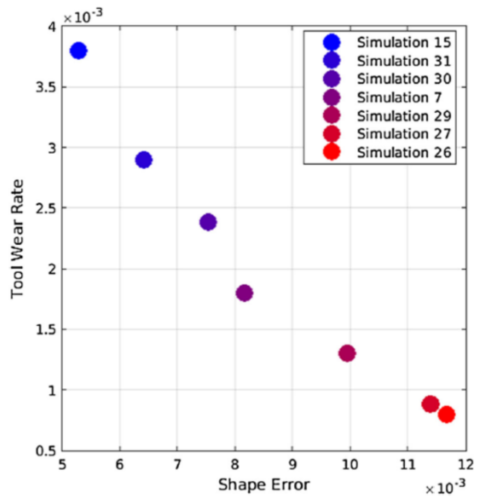
Goals: **multi-objective**,

minimize **shape error, tool wear rate**



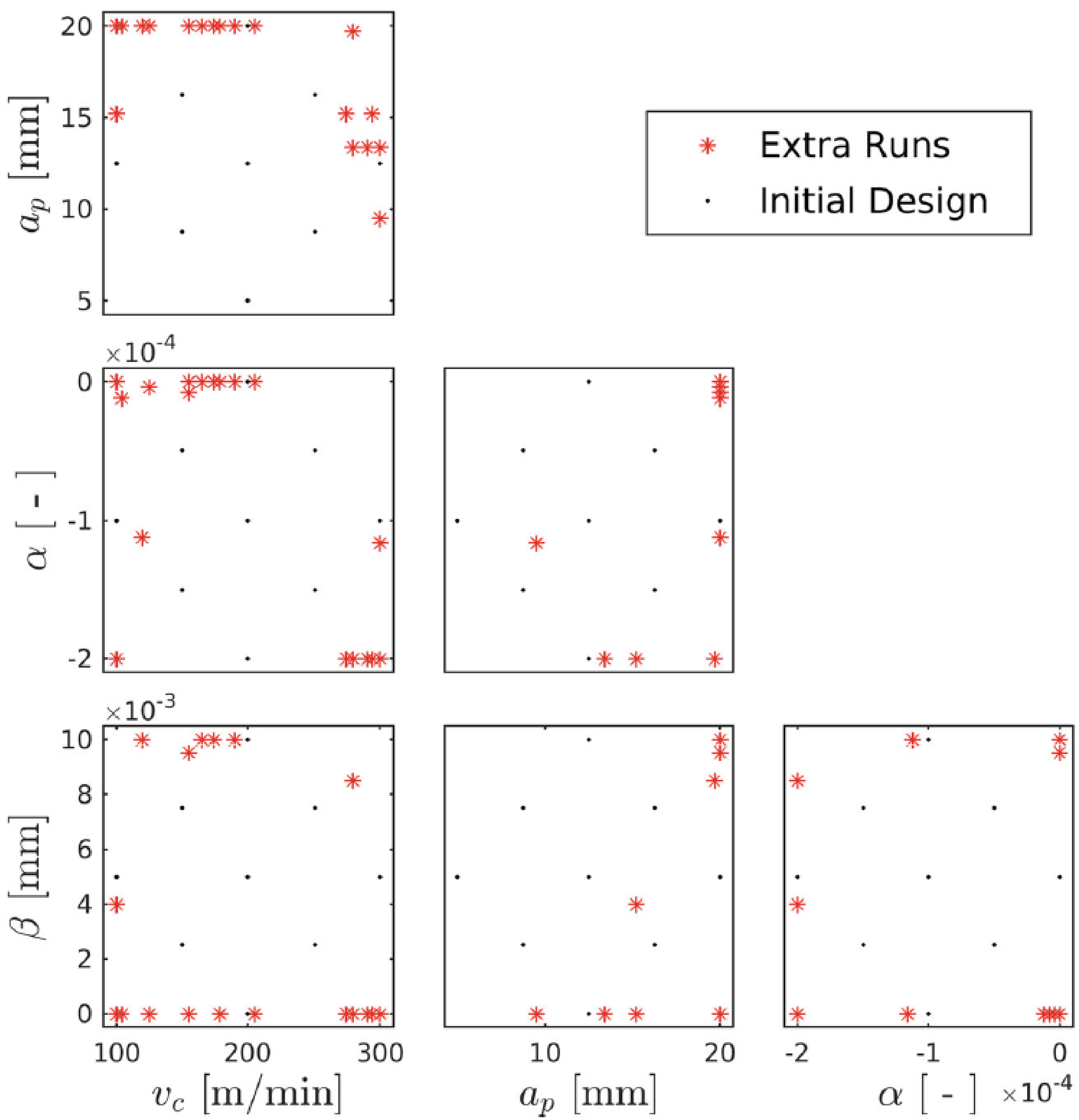




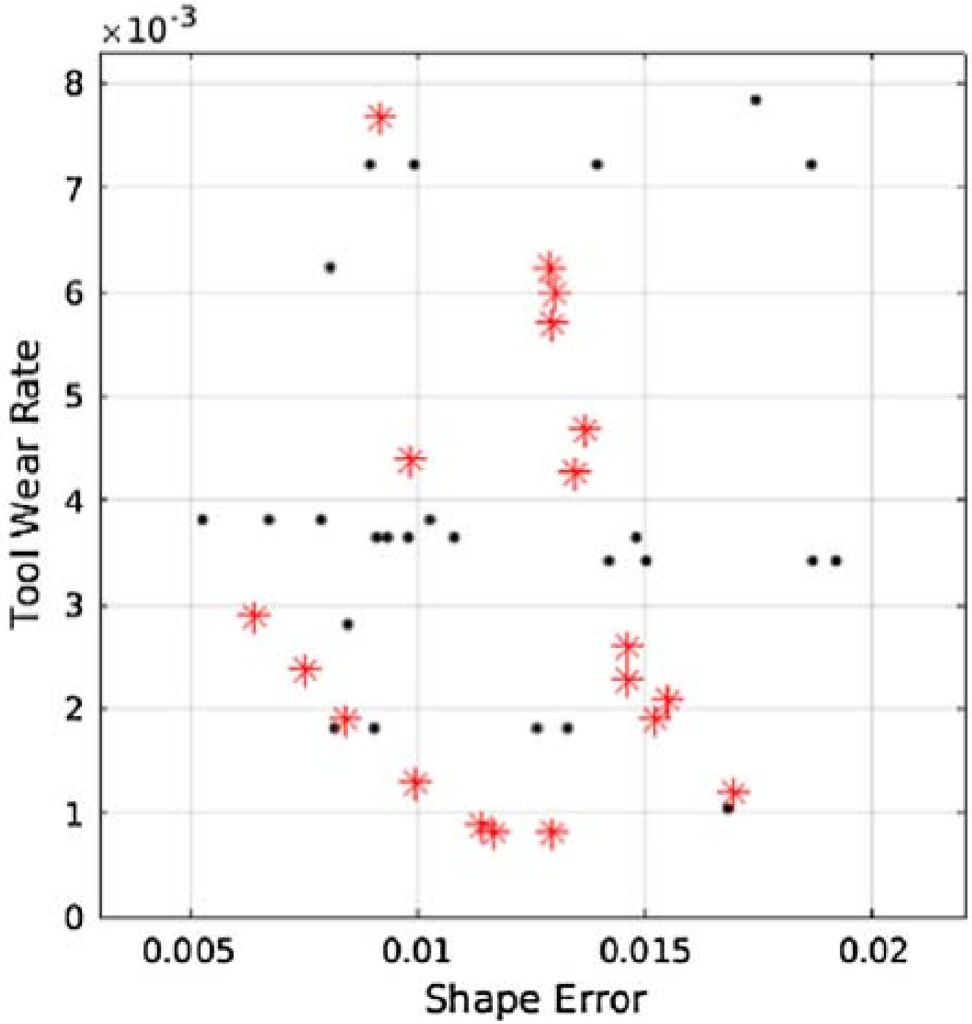


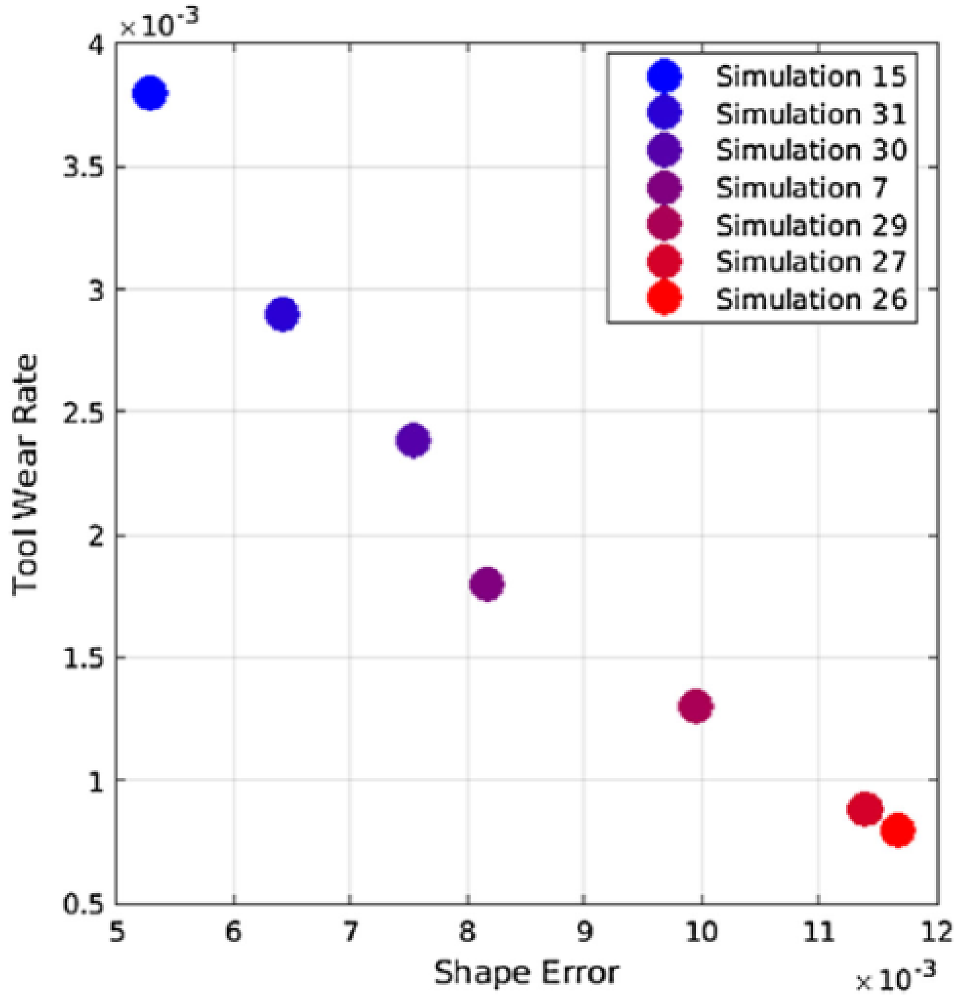
Optimization of process parameters: Simulation-based Optimization

“Simulation-based Optimization”



“Simulation-based Optimization”





Thank you for your attention!

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DFG Deutsche Forschungsgemeinschaft

DAAD Deutscher Akademischer Austauschdienst German Academic Exchange Service

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