Universität IFU Stuttgart

Verbesserung der Vorhersagegenauigkeit des Werkstoffflusses bei der Simulation von kombinierten Fließpressverfahren durch Parameterkalibrierung

Improvement of material flow prediction of combined cold forging processes by parameter calibration

10th Weimar Optimization and Stochastic Days 2013

Weimar, November 22nd 2013

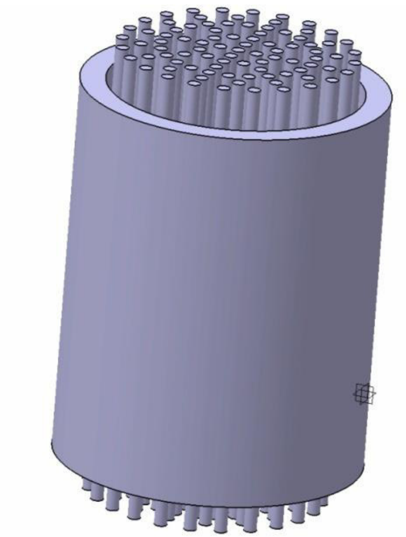
Dipl.-Ing. Christian Mletzko

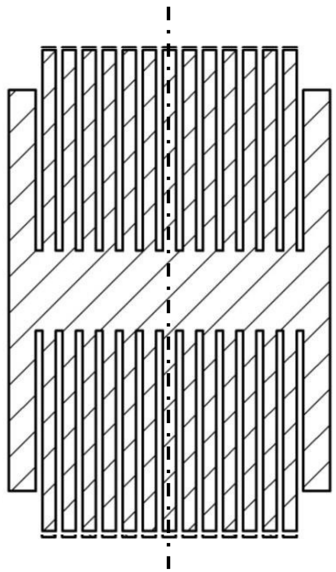
Agenda

1. Introduction
2. Experiments on backward-rod-backward-cup-extrusion
3. Sensitivity analysis of FEA simulations of backward-rod-backward-cup-extrusion
4. Inverse parameter calibration of FEA settings and comparison to experimental data
5. Conclusions

Introduction
Problem and objective

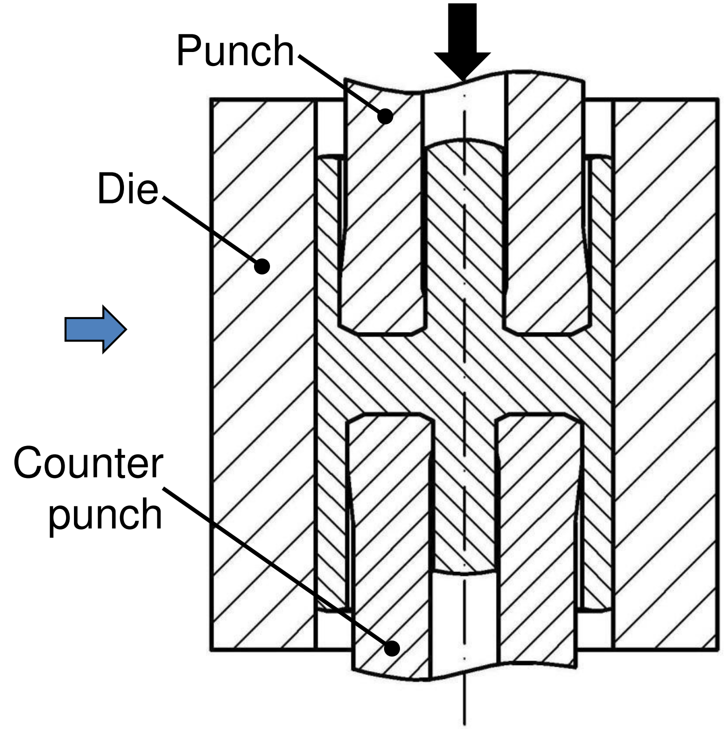
Heat dissipator





Academic part

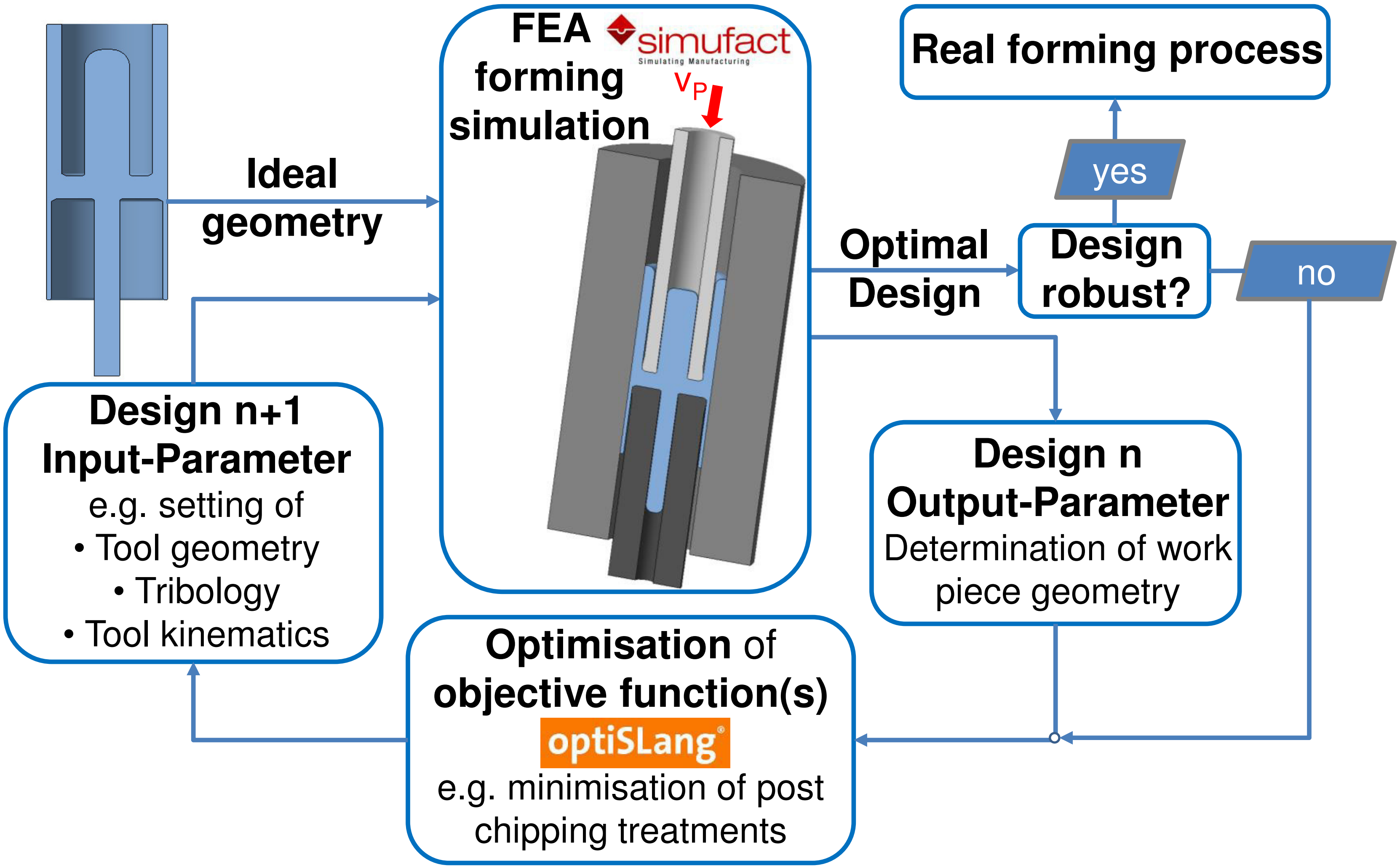
Cold forging process



Requirements:
- Combined cold forging process
- One forming stage / One stroke
- No mechanical stops

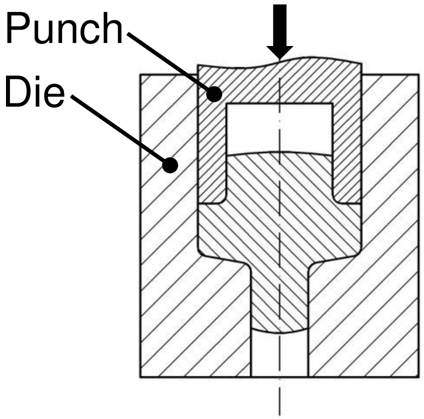
Challenge:
Production of the heat dissipator

Introduction
Procedure during automatic process optimisation



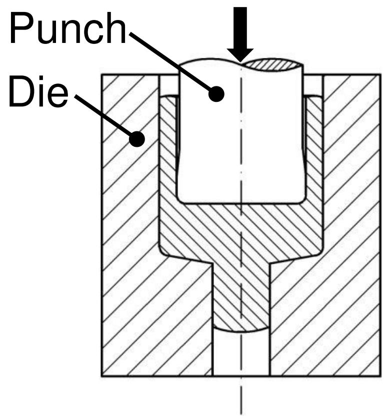
Introduction
Material flow in combined cold forging processes

Forward-Rod-Backward-Rod-Extrusion



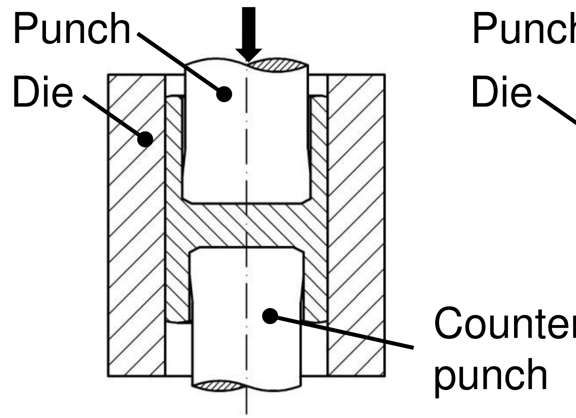
- $\varepsilon_{A,\ BR}$
- Punch radius

Forward-Rod-Backward-Cup-Extrusion



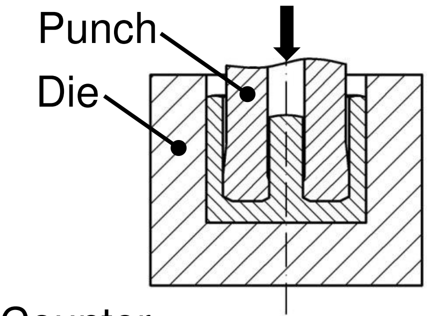
- $\varepsilon_{A,\ FR}$ und $\varepsilon_{A,\ BC}$
- Punch radius
- Die shape
- Material
- Friction

Forward-Cup-Backward-Cup-Extrusion



- $\varepsilon_{A,\ FC}$ und $\varepsilon_{A,\ BC}$
- Punch land lengths
- Punch tip radii
- Punch tip angles
- Billet height
- Material
- Friction
- Press kinematics
- Floating or driven die

Backward-Rod-Backward-Cup-Extrusion



- Material
- Friction

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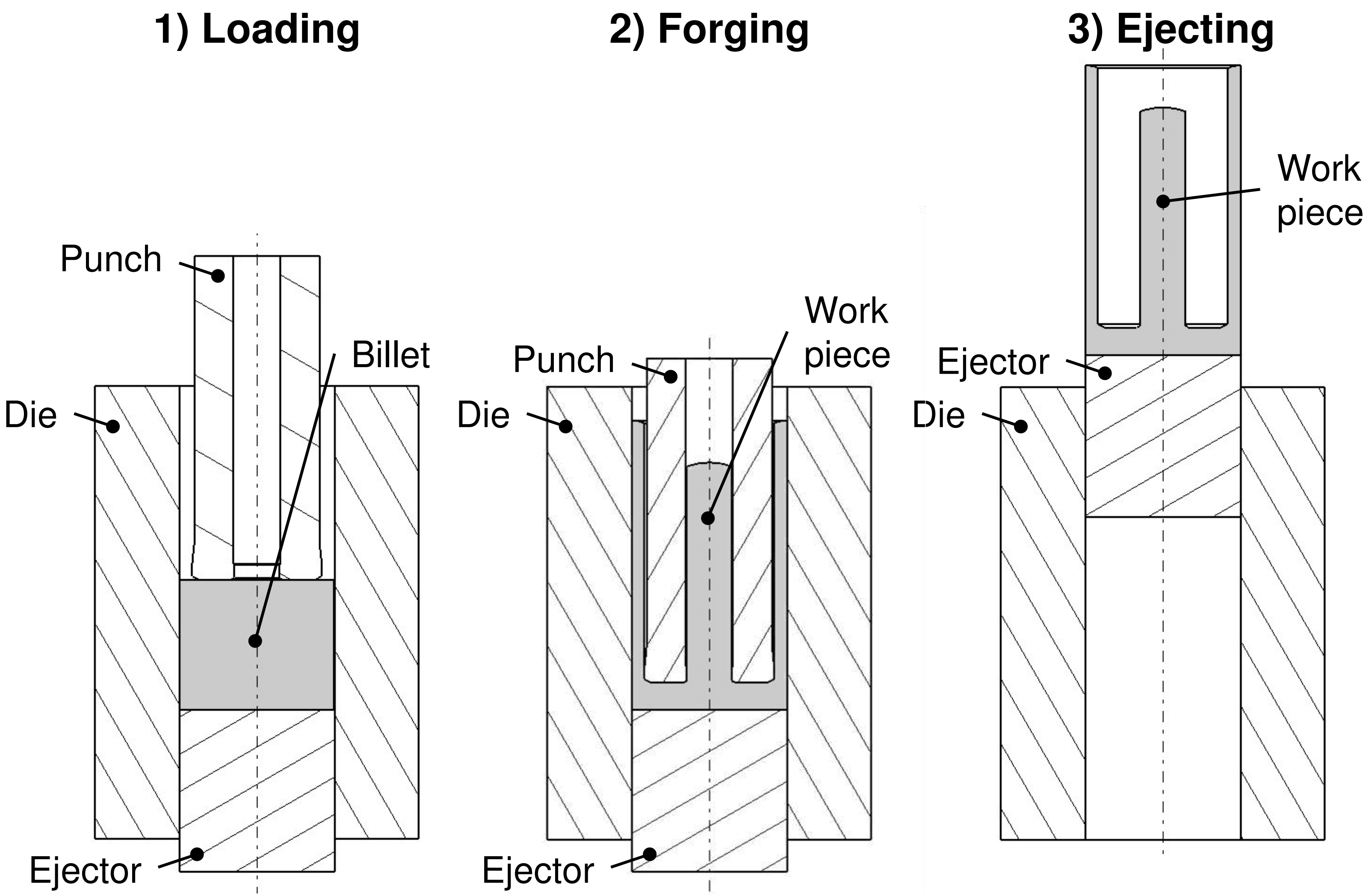
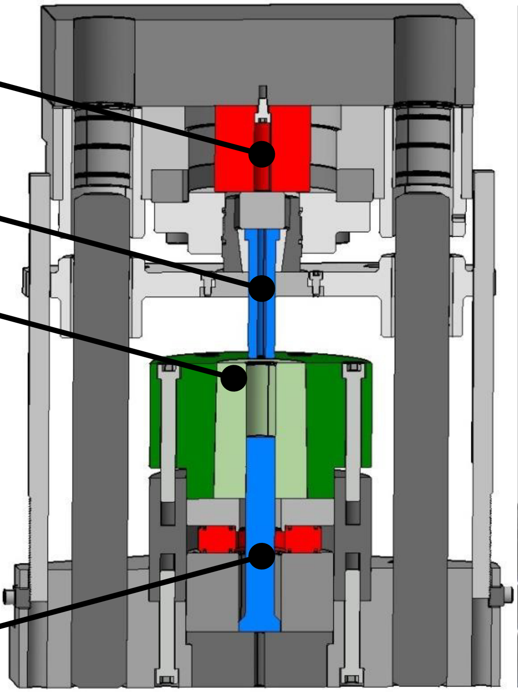
Experiments on backward-rod-backward-cup-extrusion
Process steps



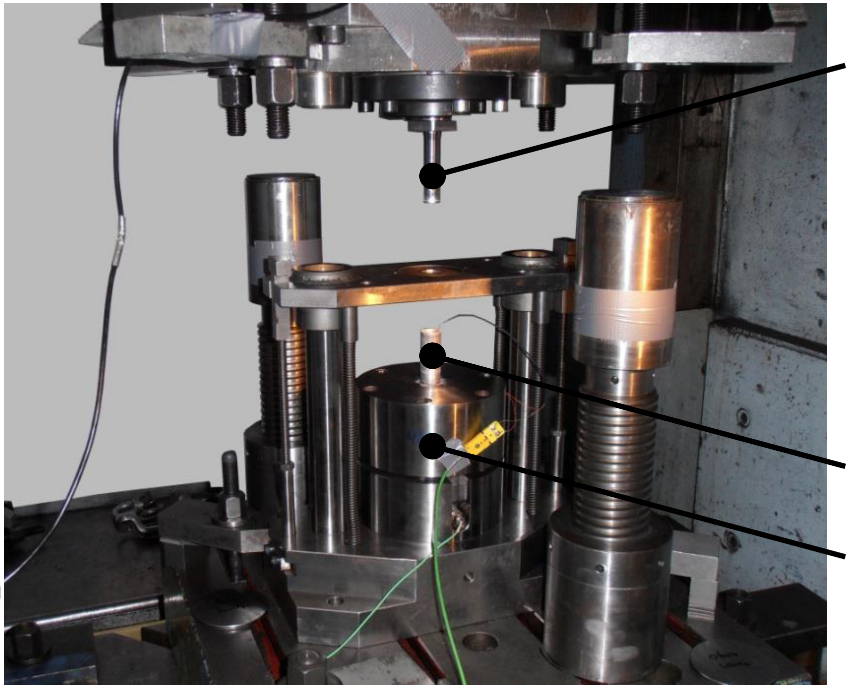
Improvement of material flow prediction of combined cold forging processes by parameter calibration

Experiments on backward-rod-backward-cup-extrusion
Test tool setup

Tool scheme

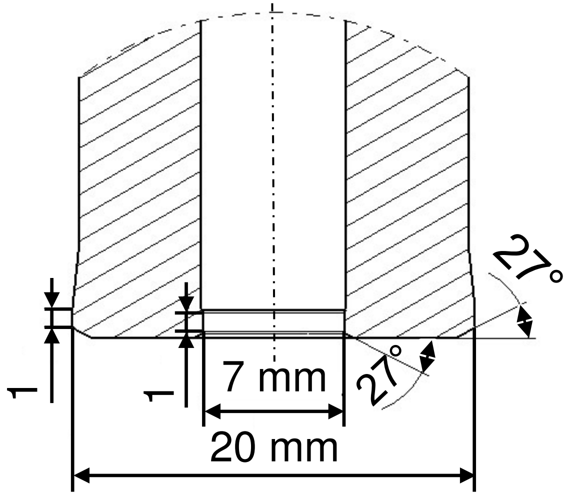


Assembled in 6.000 kN hydraulic press

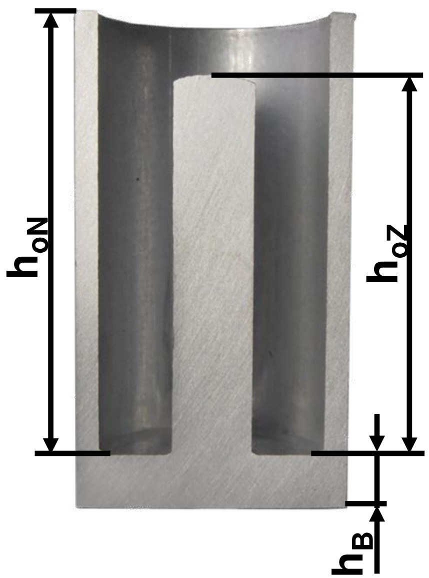


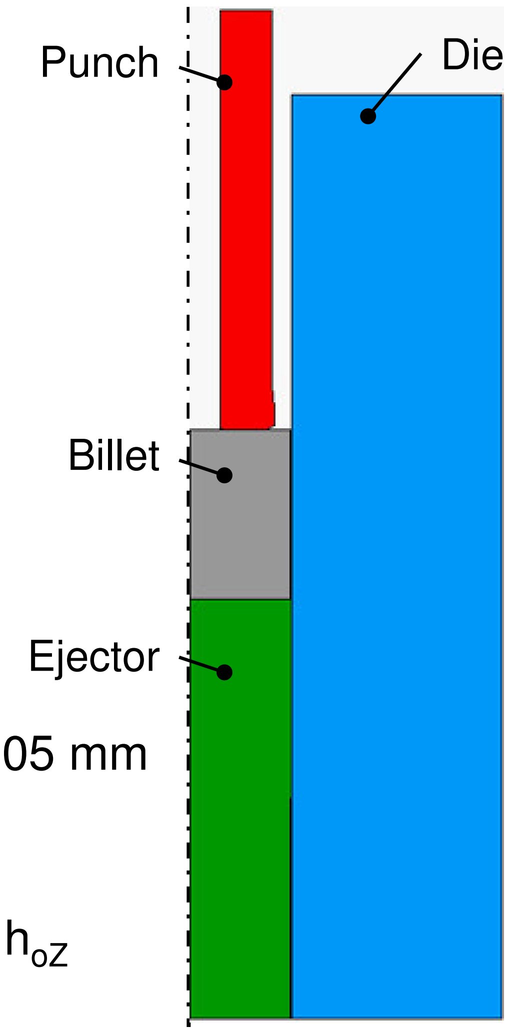
Experiments on backward-rod-backward-cup-extrusion
Test parameters and output parameters

Punch geometry



Work piece





Test parameters

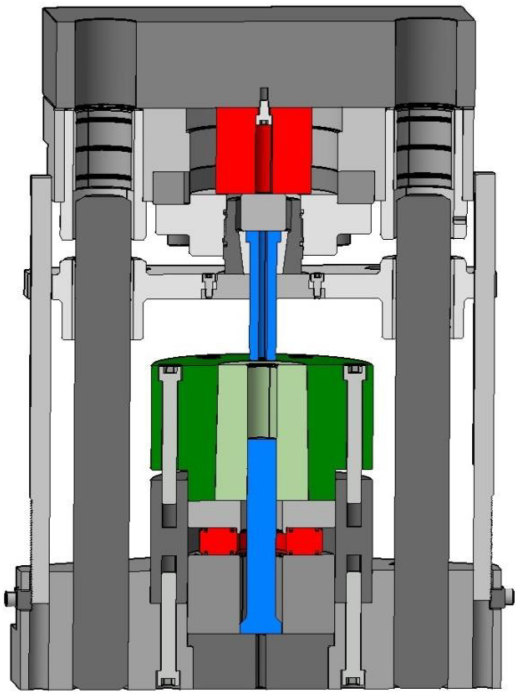
- Material: EN AW 1050A, h_0 = 20.105 mm, d_0 = 23.905 mm
- Lubricant: Zinc stearate

Output parameters

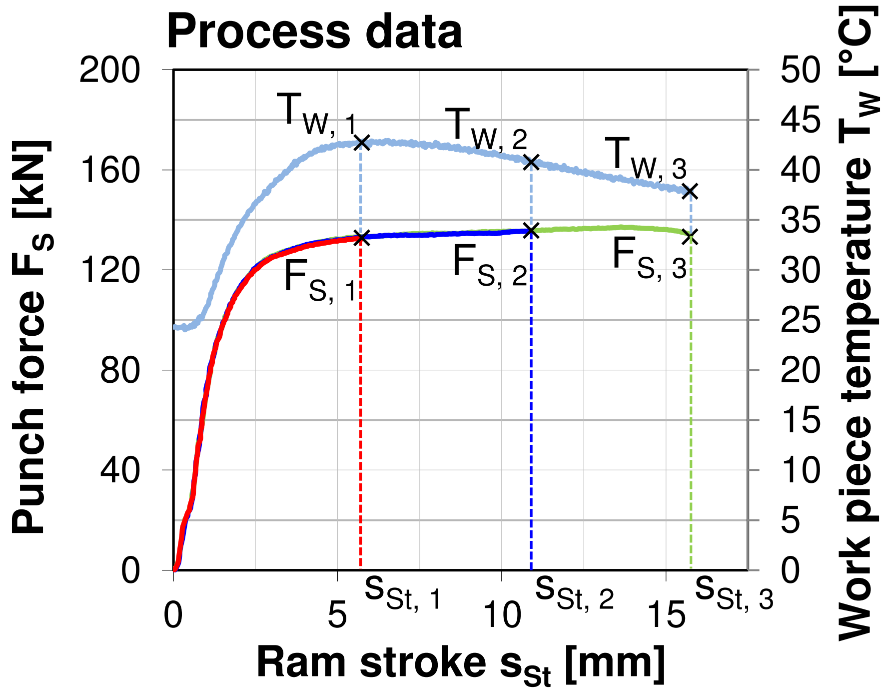
- Bottom thickness h_B, cup height h_{oN} and rod height h_{oZ}
- Punch force F_S and work piece temperature T_W

Experiments on backward-rod-backward-cup-extrusion
Experimental data

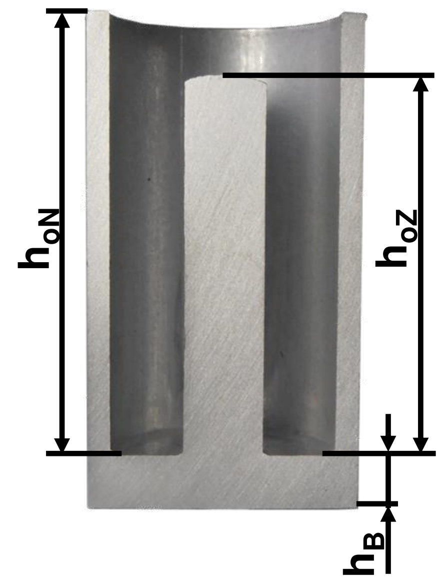
Tool scheme



Process data



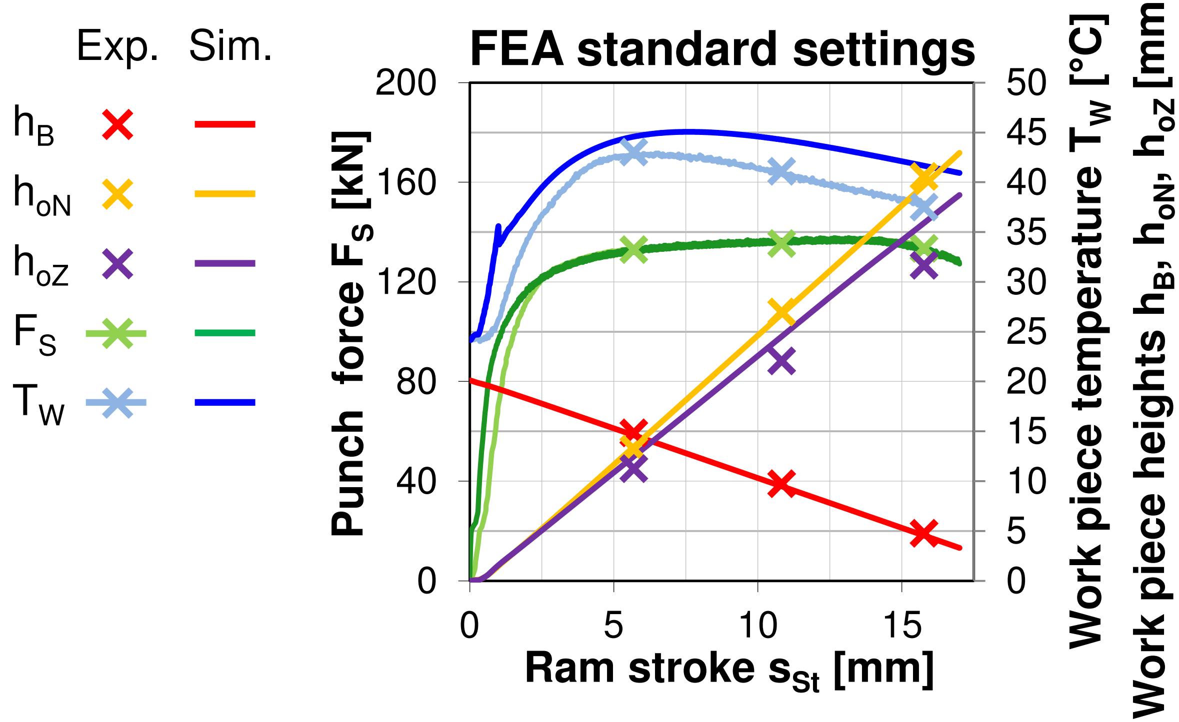
Work piece



$s_{St,1}$ [mm] = 5.71 **$s_{St,2}$ [mm] = 10.84** **$s_{St,3}$ [mm] = 15.78**

$h_{B,1}$ [mm] = 14.82	$h_{oN,1}$ [mm] = 13.18	$h_{oZ,1}$ [mm] = 11.23	$F_{S,1}$ [kN] = 132.9	$T_{W,1}$ [°C] = 43.0
$h_{B,2}$ [mm] = 9.74	$h_{oN,2}$ [mm] = 26.96	$h_{oZ,2}$ [mm] = 22.05	$F_{S,2}$ [kN] = 135.3	$T_{W,2}$ [°C] = 41.1
$h_{B,3}$ [mm] = 4.74	$h_{oN,3}$ [mm] = 40.56	$h_{oZ,3}$ [mm] = 31.65	$F_{S,3}$ [kN] = 133.4	$T_{W,3}$ [°C] = 37.5
with Δh_B = 0.1 mm	with Δh_{oN} = 0.1 mm	with Δh_{oZ} = 0.1 mm	with ΔF_S = 5 kN	with ΔT_W = 3 °C

Experiments on backward-rod-backward-cup-extrusion
Experiments vs. FEA simulation



	Exp.	Sim.
$h_{B,1}$ [mm]	14.82	14.59
$h_{B,2}$ [mm]	9.74	9.47
$h_{B,3}$ [mm]	4.74	4.52
$h_{oN,1}$ [mm]	13.18	13.49
$h_{oN,2}$ [mm]	26.96	26.80
$h_{oN,3}$ [mm]	40.56	39.73
$h_{oZ,1}$ [mm]	11.23	12.51
$h_{oZ,2}$ [mm]	22.05	24.55
$h_{oZ,3}$ [mm]	31.65	35.94
$F_{S,1}$ [kN]	132.9	131.9
$F_{S,2}$ [kN]	135.3	135.6
$F_{S,3}$ [kN]	133.4	133.3
$T_{W,1}$ [°C]	43.0	44.6
$T_{W,2}$ [°C]	41.1	44.3
$T_{W,3}$ [°C]	37.5	41.7

$D = \infty$ N/mm
$\mu = 0.03$
$m = 0.18$
$\alpha = 20000$ W/(m²·K)
$V = 0.750$

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2. Experiments on backward-rod-backward-cup-extrusion
3. Sensitivity analysis of FEA simulations of backward-rod-backward-cup-extrusion
4. Inverse parameter calibration of FEA settings and comparison to experimental data
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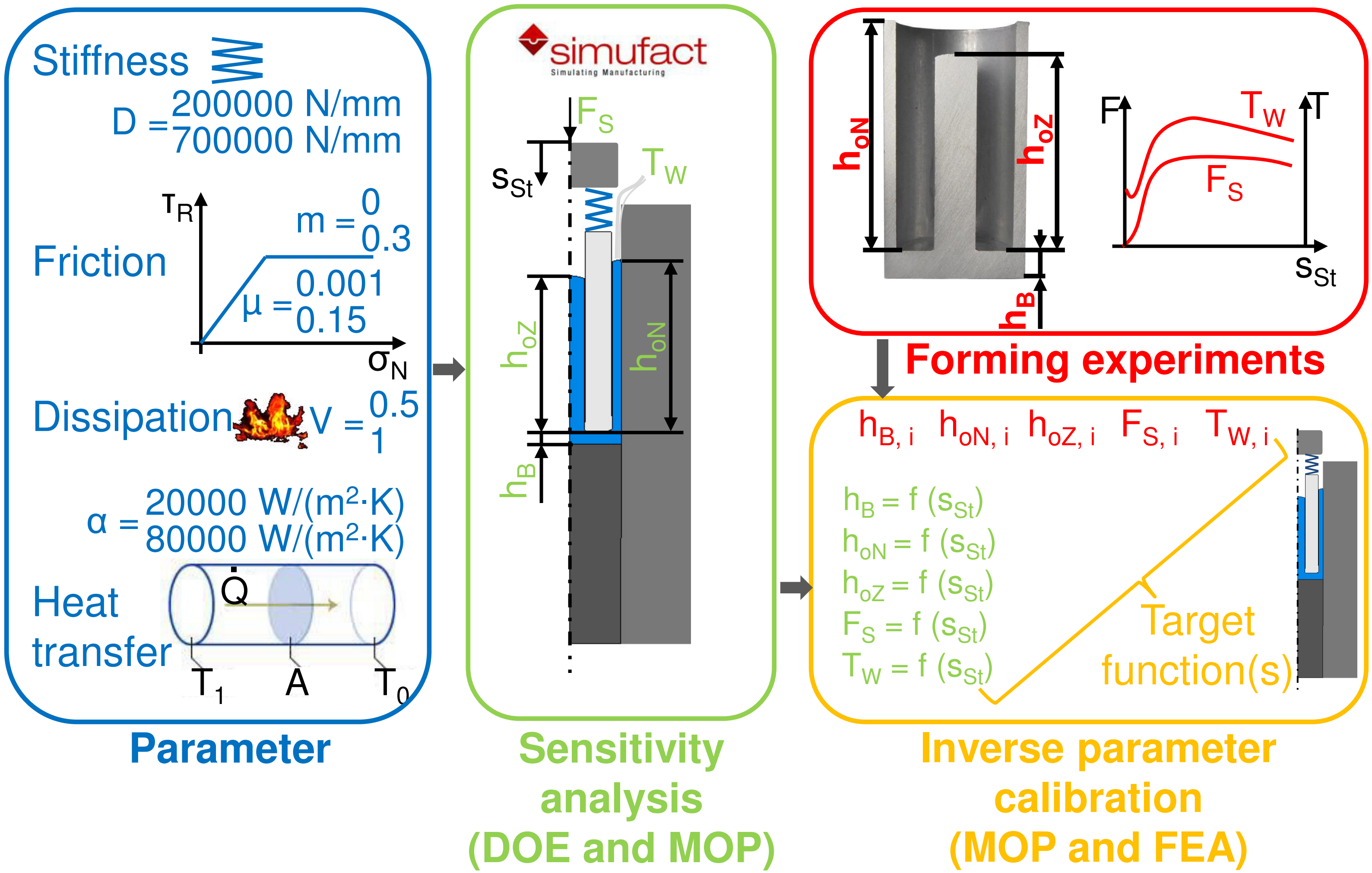
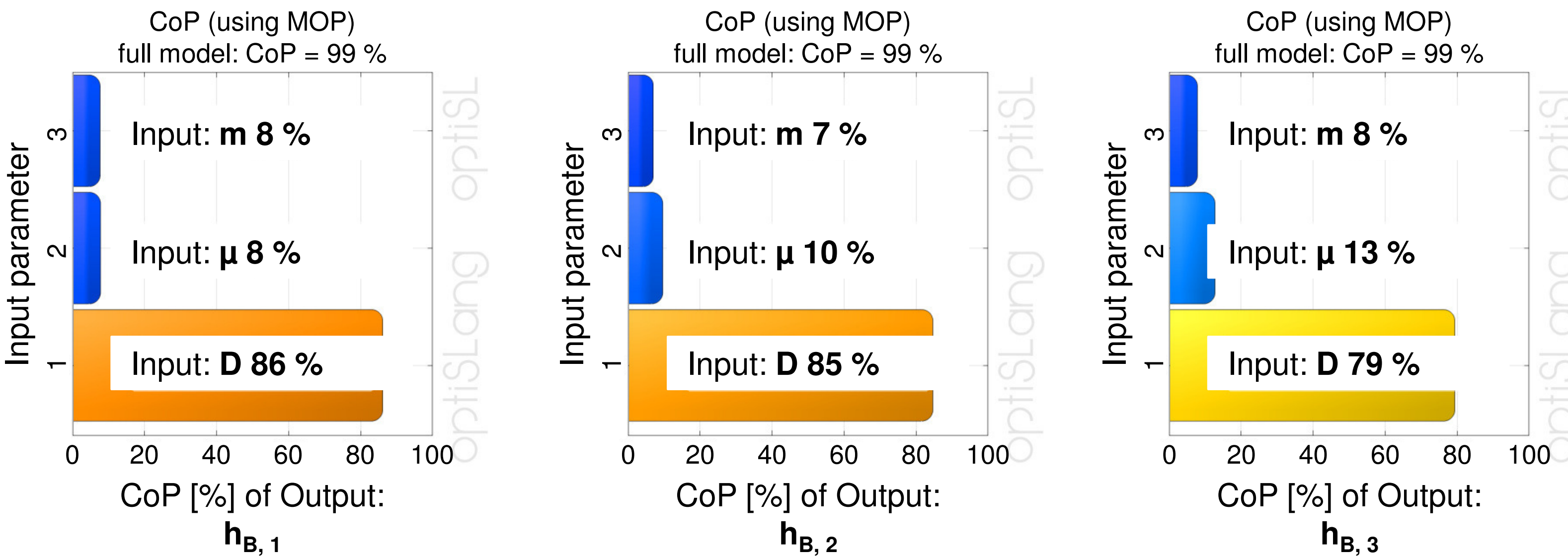
Sensitivity analysis of FEA simulations
Way of procedure



Sensitivity analysis of FEA simulations
MOP results: Work piece bottom thickness

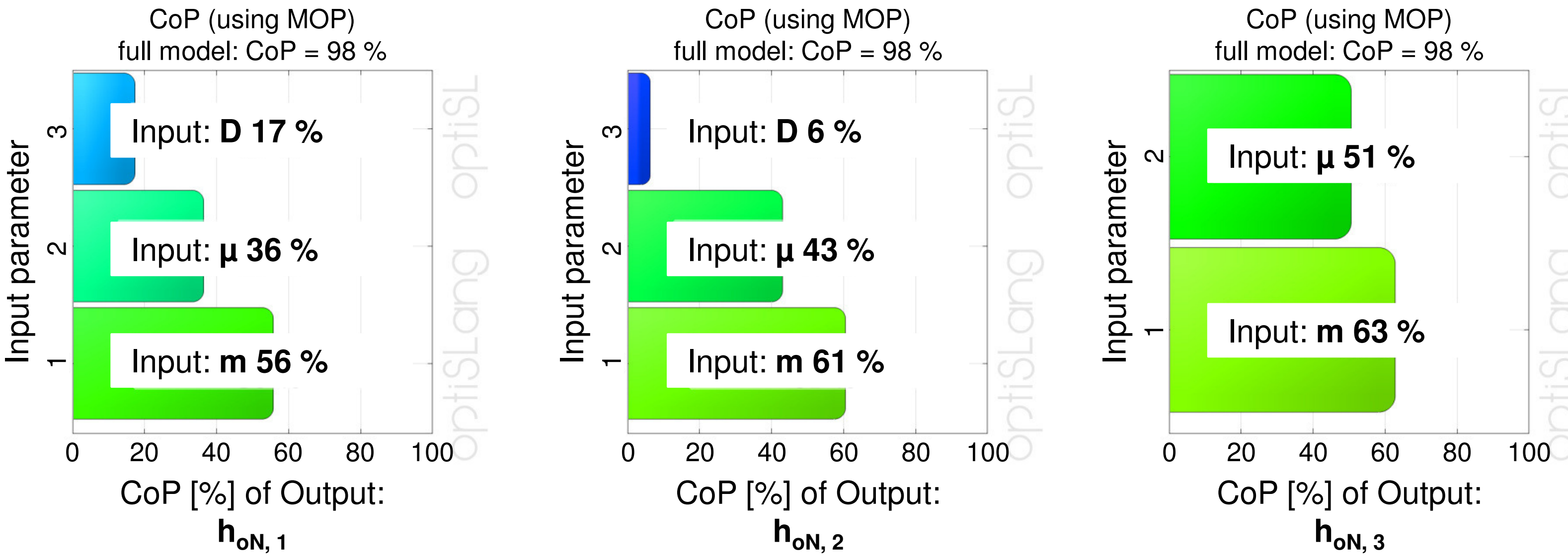
MOP settings: 5 input parameters, 77 support points, 39 test points, Δ CoP = 0.03



- Work piece bottom thickness $h_{B,\,i}$ depends mainly on the press and tool stiffness D
- $h_{B,\,i}$ depends also on the friction parameters μ and m
- Very good Coefficients of Prognosis
- Strong correlation between $h_{B,\,1}$, $h_{B,\,2}$ and $h_{B,\,3}$

Sensitivity analysis of FEA simulations
MOP results: Cup height

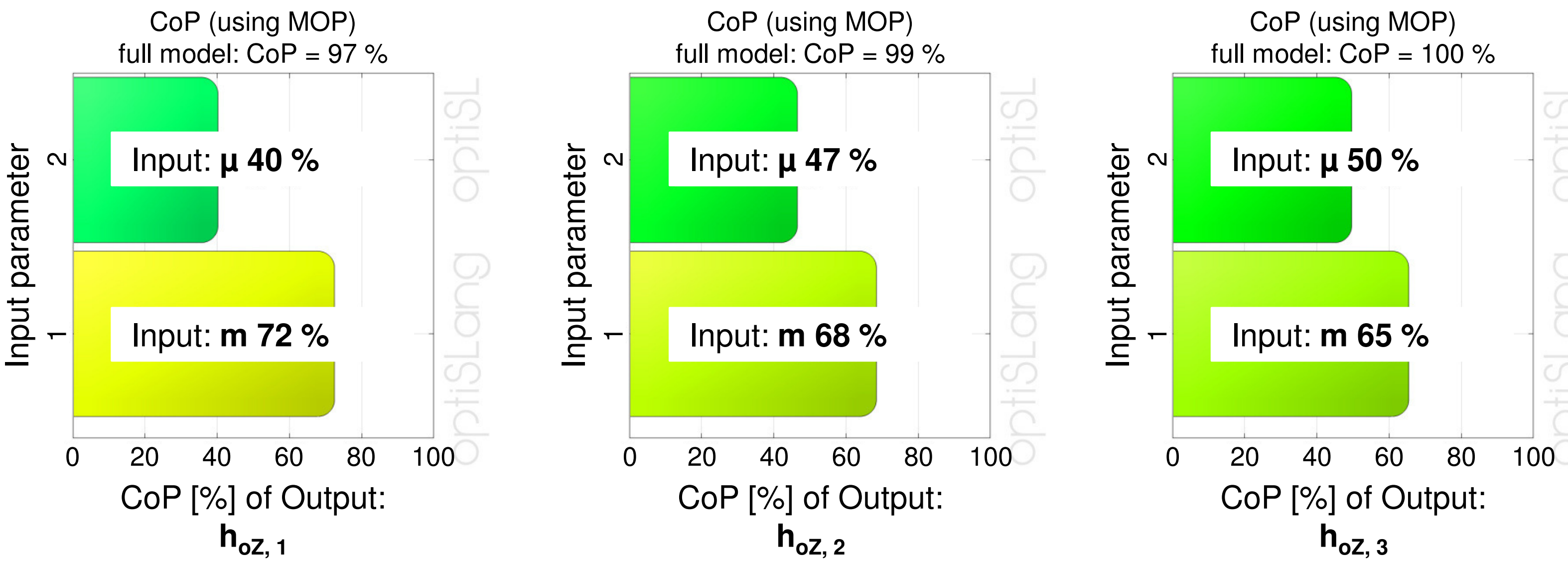
MOP settings: 5 input parameters, 77 support points, 39 test points, Δ CoP = 0.03



- Cup height $h_{oN,i}$ depends mainly on the friction parameters μ and m
- $h_{oN,1}$ and $h_{oN,2}$ depends also on the press and tool stiffness D
- Very good Coefficients of Prognosis
- Strong correlation between $h_{oN,1}$, $h_{oN,2}$ and $h_{oN,3}$

Sensitivity analysis of FEA simulations
MOP results: Rod height

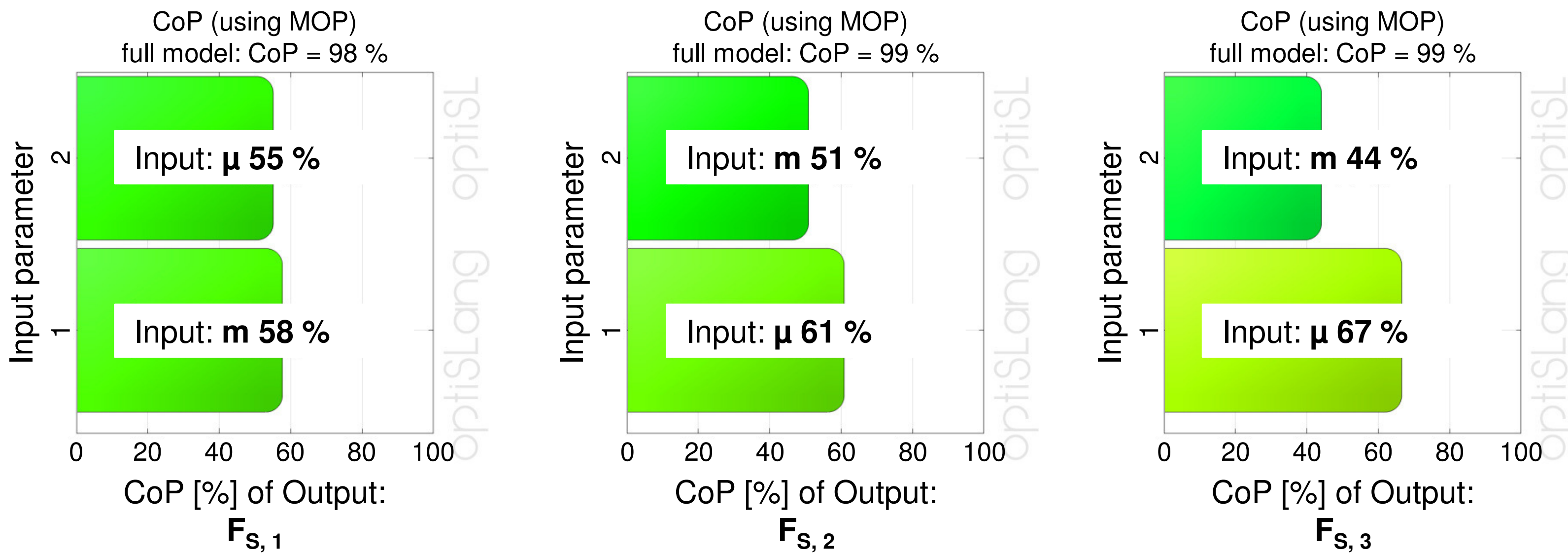
MOP settings: 5 input parameters, 77 support points, 39 test points, Δ CoP = 0.03



- Rod height $h_{oZ,i}$ depends on the friction parameters μ and m
- Very good Coefficients of Prognosis
- Strong correlation between $h_{oZ,1}$, $h_{oZ,2}$ and $h_{oZ,3}$

Sensitivity analysis of FEA simulations
MOP results: Punch force

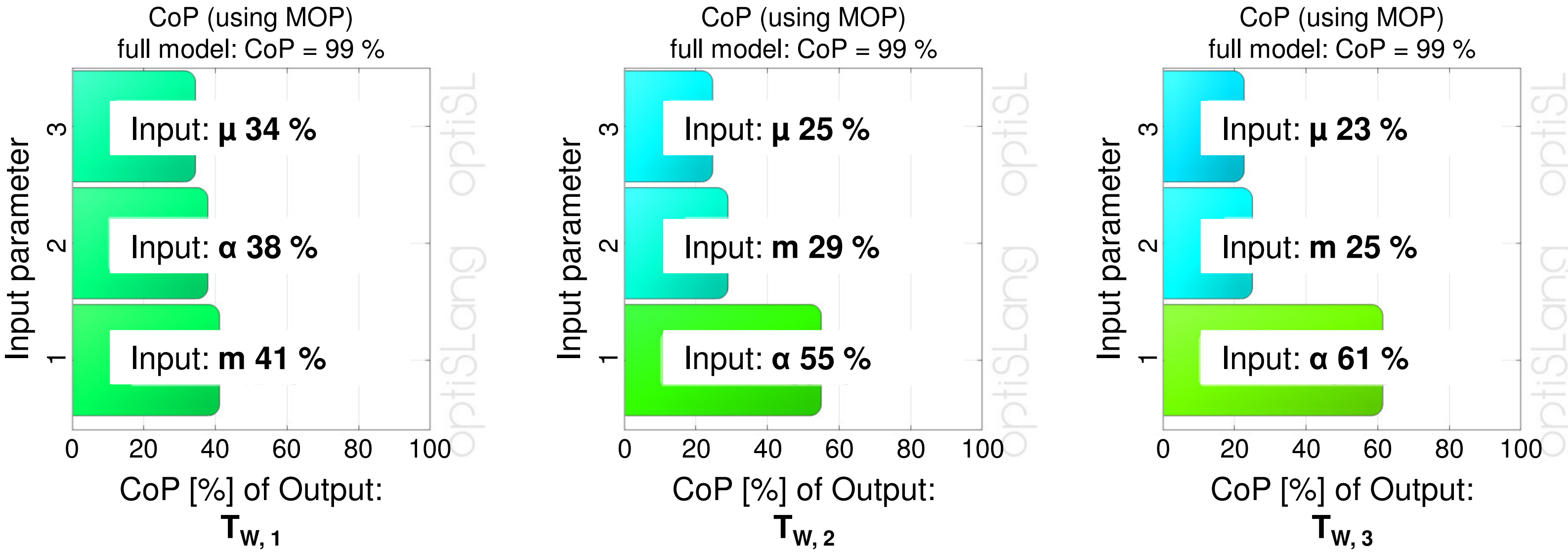
MOP settings: 5 input parameters, 77 support points, 39 test points, Δ CoP = 0.03



- Punch force $F_{S,i}$ depends on the friction parameters μ and m
- Very good Coefficients of Prognosis
- Strong correlation between $F_{S,1}$, $F_{S,2}$ and $F_{S,3}$

Sensitivity analysis of FEA simulations
MOP results: Work piece temperature

MOP settings: 5 input parameters, 77 support points, 39 test points, Δ CoP = 0.03



- Work piece temperature $T_{W,i}$ depends on the heat transfer coefficients α and friction parameters μ and m
- Very good Coefficients of Prognosis
- Strong correlation between $T_{W,1}$, $T_{W,2}$ and $T_{W,3}$

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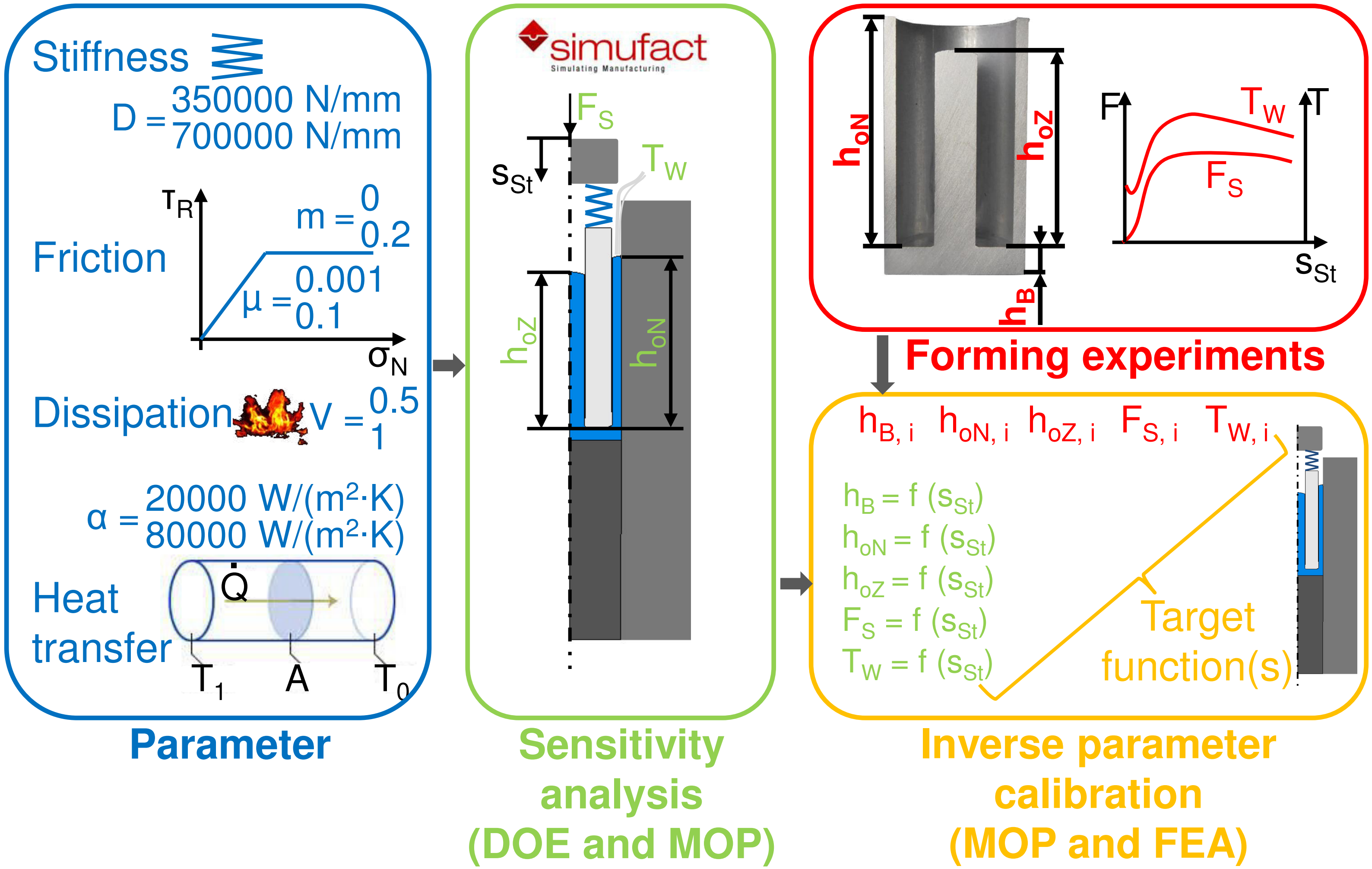
Inverse parameter calibration of FEA settings
Way of procedure



Inverse parameter calibration of FEA settings
Objective functions

Bottom thickness failure: $Err\_h_B = \frac{1}{3} \cdot \sum_{i=1}^{3} \left(\frac{h_{B,\,i\,exp} - h_{B,\,i\,sim}}{0.1\,mm} \right)^2$ with $\Delta h_B = 0.1$ mm

Material flow failure: $Err\_h_{oN} = \frac{1}{3} \cdot \sum_{i=1}^{3} \left(\frac{h_{oN,\,i\,exp} - h_{oN,\,i\,sim}}{0.1\,mm} \right)^2$ with $\Delta h_{oN} = 0.1$ mm

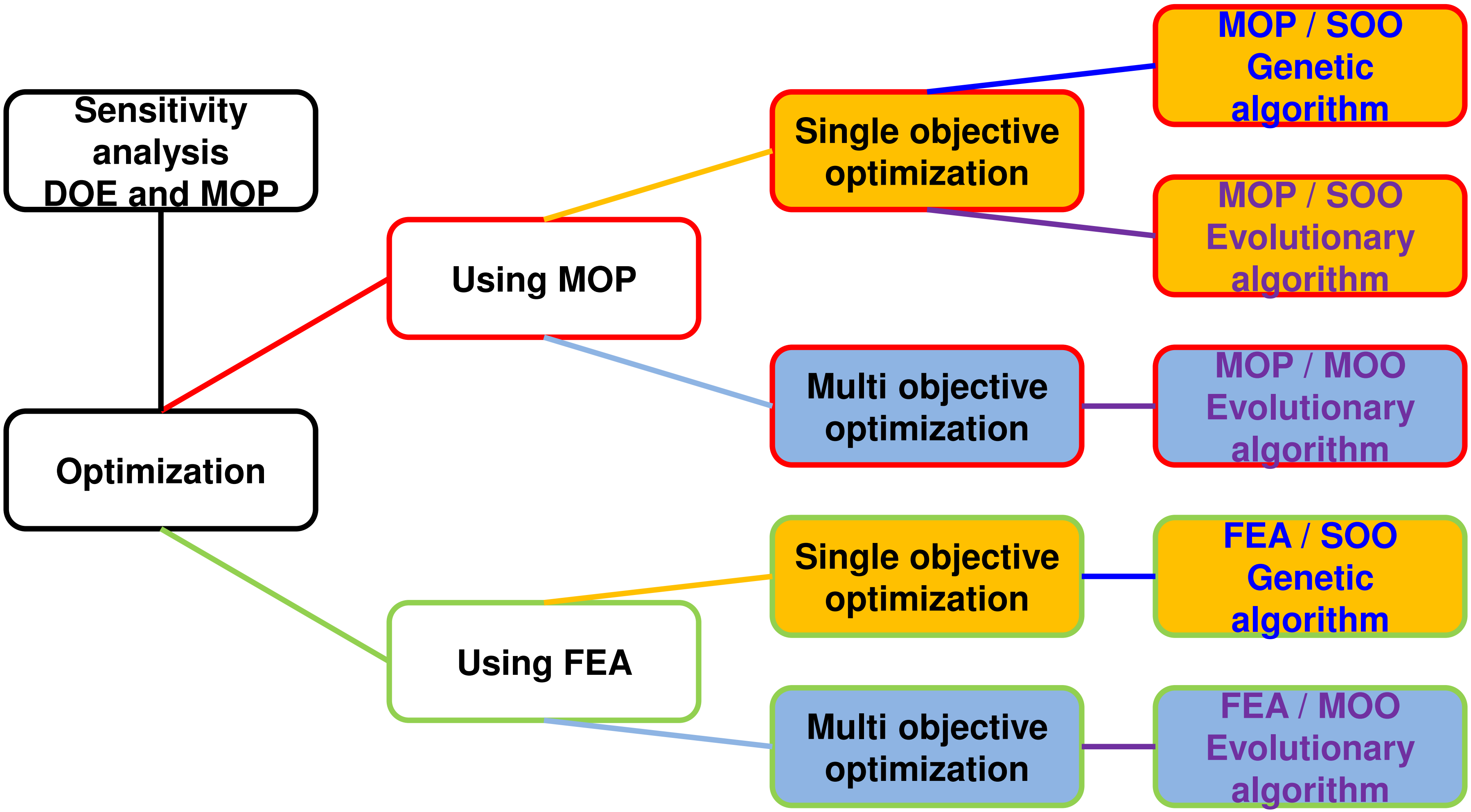
Material flow failure: $Err\_h_{oZ} = \frac{1}{3} \cdot \sum_{i=1}^{3} \left(\frac{h_{oZ,\,i\,exp} - h_{oZ,\,i\,sim}}{0.1\,mm} \right)^2$ with $\Delta h_{oZ} = 0.1$ mm

Force failure: $Err\_F_S = \frac{1}{3} \cdot \sum_{i=1}^{3} \left(\frac{F_{S,\,i\,exp} - F_{S,\,i\,sim}}{5\,kN} \right)^2$ with $\Delta F_S = 5$ kN

Temperature failure: $Err\_T_W = \frac{1}{3} \cdot \sum_{i=1}^{3} \left(\frac{T_{i\,exp} - T_{i\,sim}}{3\,°C} \right)^2$ with $\Delta T_W = 3$ °C

Failure sum: $Err = Err\_h_B + Err\_h_{oN} + Err\_h_{oZ} + Err\_F_S + Err\_T_W$

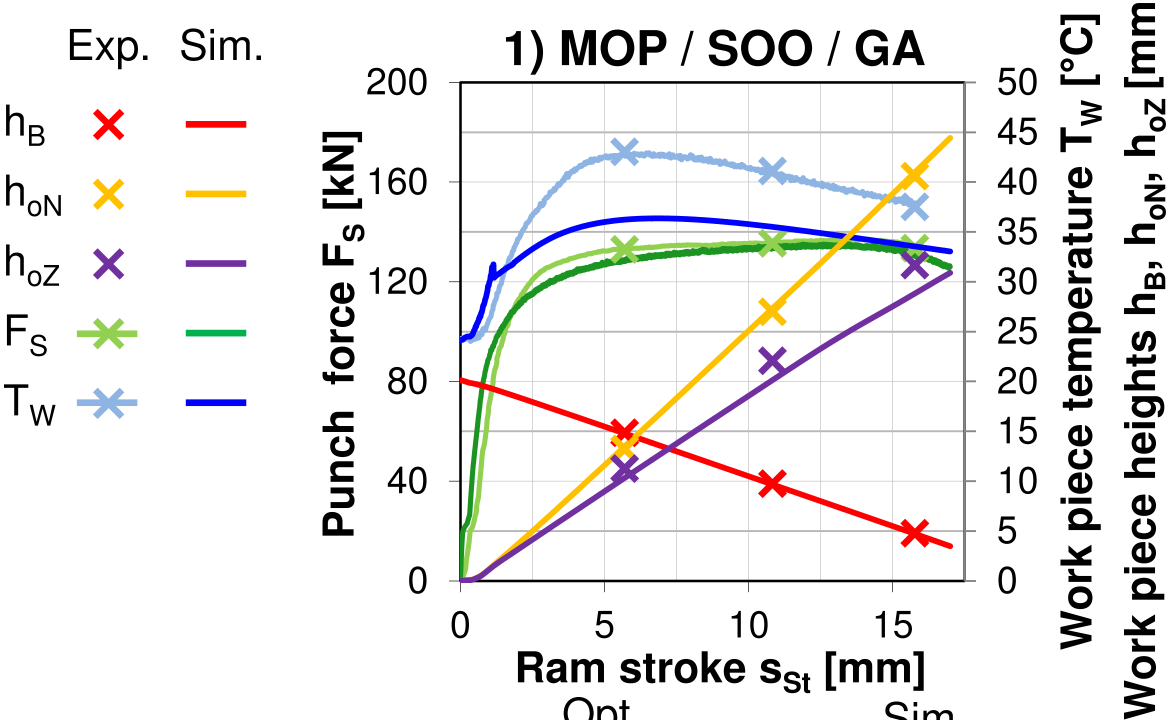
Inverse parameter calibration of FEA settings
Conducted variants



Inverse parameter calibration of FEA settings
Input parameters after calibration runs

	D [N/mm]	**µ** [-]	**m** [-]	**α** [W/(m2·K)]	**V** [-]	**Err** [-]
MOP / SOO Genetic algorithm	684060	0.001	0.118	25894	0.5	3.73
MOP / SOO Evolutionary algorithm	684420	0.001	0.119	26878	0.5	3.73
MOP / MOO Evolutionary algorithm	547670	0.006	0.042	34749	0.791	38.66
FEA / SOO Genetic algorithm	640890	0.023	0.040	68257	0.738	9.27
FEA / MOO Evolutionary algorithm	593550	0.022	0.053	29368	0.587	26.89

Inverse parameter calibration of FEA settings
MOP / Single objective optimization / Genetic algorithm

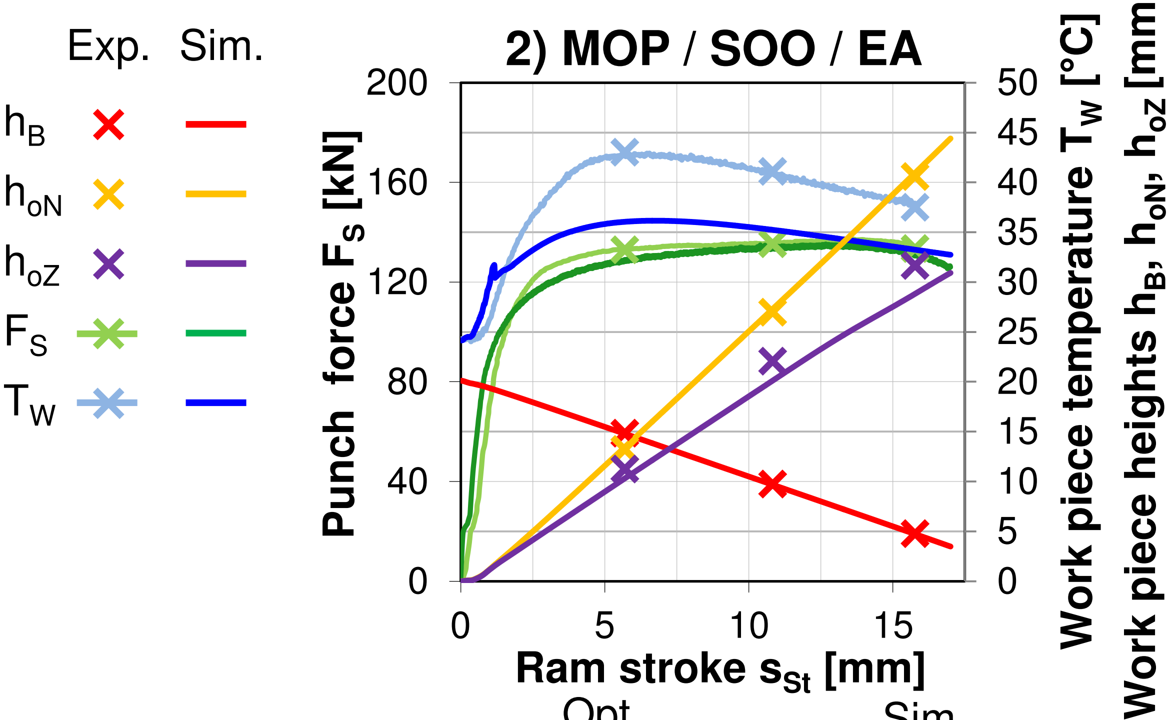


D = 684060 N/mm
μ = 0.001
m = 0.118
α = 25894 W/(m²·K)
V = 0.500

Opt.	Sim.
Err_h_B = 0.84	Err_h_B = 0.34
Err_h_{oN} = 1.71	Err_h_{oN} = 14.86
Err_h_{oZ} = 0.30	Err_h_{oZ} = 412.88
Err_F_S = 0.85	Err_F_S = 0.48
Err_T_W = 0.03	Err_T_W = 3.44
Err = 3.73	**Err = 432.00**

	Exp.	Opt.	Sim.
$h_{B,1}$ [mm]	14.82	14.76	14.77
$h_{B,2}$ [mm]	9.74	9.63	9.66
$h_{B,3}$ [mm]	4.74	4.68	4.71
$h_{oN,1}$ [mm]	13.18	13.32	13.50
$h_{oN,2}$ [mm]	26.96	26.98	27.35
$h_{oN,3}$ [mm]	40.56	40.38	41.00
$h_{oZ,1}$ [mm]	11.23	11.21	10.34
$h_{oZ,2}$ [mm]	22.05	21.96	20.14
$h_{oZ,3}$ [mm]	31.65	31.68	28.83
$F_{S,1}$ [kN]	132.9	128.2	128.1
$F_{S,2}$ [kN]	135.3	131.5	133.6
$F_{S,3}$ [kN]	133.4	128.2	130.3
$T_{W,1}$ [°C]	43.0	42.4	36.2
$T_{W,2}$ [°C]	41.1	41.1	35.5
$T_{W,3}$ [°C]	37.5	38.1	33.5

Inverse parameter calibration of FEA settings
MOP / Single objective optimization / Evolutionary algorithm



	Exp.	Opt.	Sim.
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$h_{B,2}$ [mm]	9.74	9.63	9.66
$h_{B,3}$ [mm]	4.74	4.68	4.71
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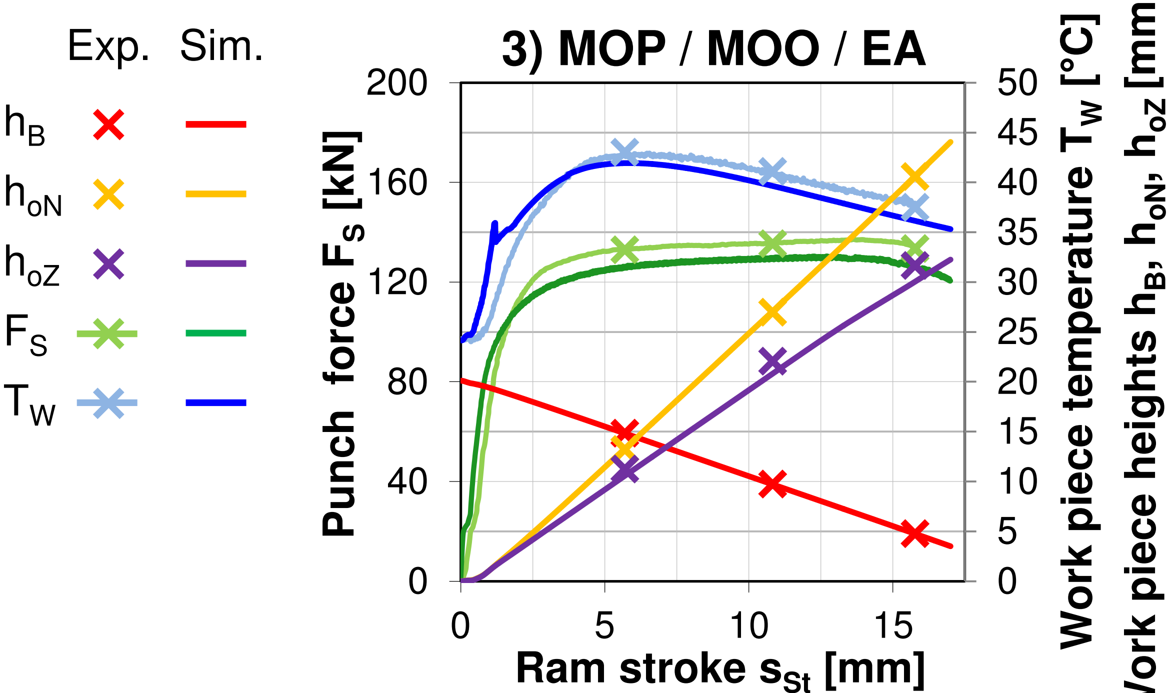
$h_{oN,2}$ [mm]	26.96	26.98	27.35
$h_{oN,3}$ [mm]	40.56	40.38	41.00
$h_{oZ,1}$ [mm]	11.23	11.21	10.34
$h_{oZ,2}$ [mm]	22.05	21.96	20.14
$h_{oZ,3}$ [mm]	31.65	31.68	28.83
$F_{S,1}$ [kN]	132.9	128.2	128.1
$F_{S,2}$ [kN]	135.3	131.5	133.6
$F_{S,3}$ [kN]	133.4	128.2	130.3
$T_{W,1}$ [°C]	43.0	42.3	36.2
$T_{W,2}$ [°C]	41.1	41.0	35.5
$T_{W,3}$ [°C]	37.5	38.0	33.5

D = 684420 N/mm
μ = 0.001
m = 0.119
α = 26878 W/(m²·K)
V = 0.500

Opt.	Sim.
Err_h_B = 0.84	Err_h_B = 0.33
Err_h_{oN} = 1.72	Err_h_{oN} = 13.34
Err_h_{oZ} = 0.30	Err_h_{oZ} = 412.51
Err_F_S = 0.84	Err_F_S = 0.38
Err_T_W = 0.03	Err_T_W = 3.74
Err = 3.73	**Err = 430.30**

Inverse parameter calibration of FEA settings
MOP / Multi objective optimization / Evolutionary algorithm

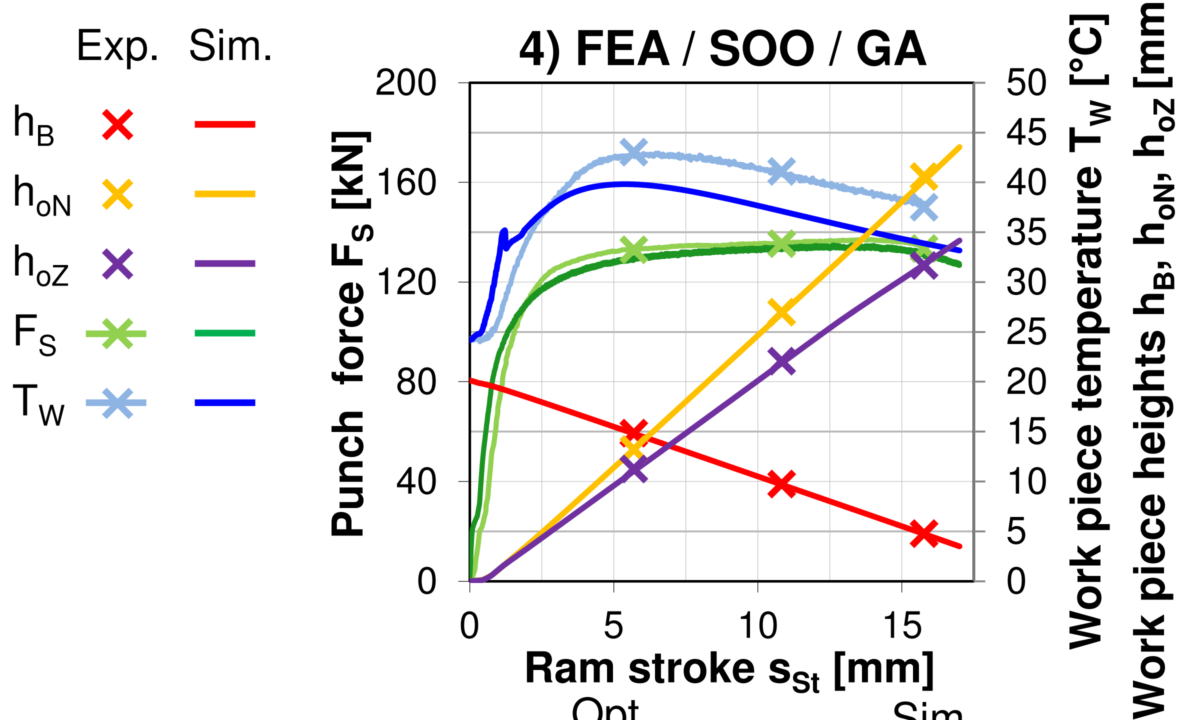


D = 547670 N/mm
μ = 0.006
m = 0.042
α = 34749 W/(m²·K)
V = 0.791

	Opt.	Sim.
	Err_h_B = 0.29	Err_h_B = 0.08
	Err_h_{oN} = 17.62	Err_h_{oN} = 1.60
	Err_h_{oZ} = 20.64	Err_h_{oZ} = 146.93
	Err_F_S = 0.07	Err_F_S = 1.84
	Err_T_W = 0.04	Err_T_W = 0.19
	Err = 38.66	**Err = 150.64**

	Exp.	Opt.	Sim.
$h_{B,1}$ [mm]	14.82	14.83	14.81
$h_{B,2}$ [mm]	9.74	9.71	9.69
$h_{B,3}$ [mm]	4.74	4.77	4.74
$h_{oN,1}$ [mm]	13.18	13.07	13.32
$h_{oN,2}$ [mm]	26.96	26.55	27.10
$h_{oN,3}$ [mm]	40.56	39.89	40.64
$h_{oZ,1}$ [mm]	11.23	10.95	10.60
$h_{oZ,2}$ [mm]	22.05	21.94	20.84
$h_{oZ,3}$ [mm]	31.65	32.32	30.06
$F_{S,1}$ [kN]	132.9	130.6	125.6
$F_{S,2}$ [kN]	135.3	135.3	129.9
$F_{S,3}$ [kN]	133.4	133.4	126.0
$T_{W,1}$ [°C]	43.0	42.6	41.9
$T_{W,2}$ [°C]	41.1	41.3	39.6
$T_{W,3}$ [°C]	37.5	38.3	36.1

Inverse parameter calibration of FEA settings
FEA / Single objective optimization / Genetic algorithm

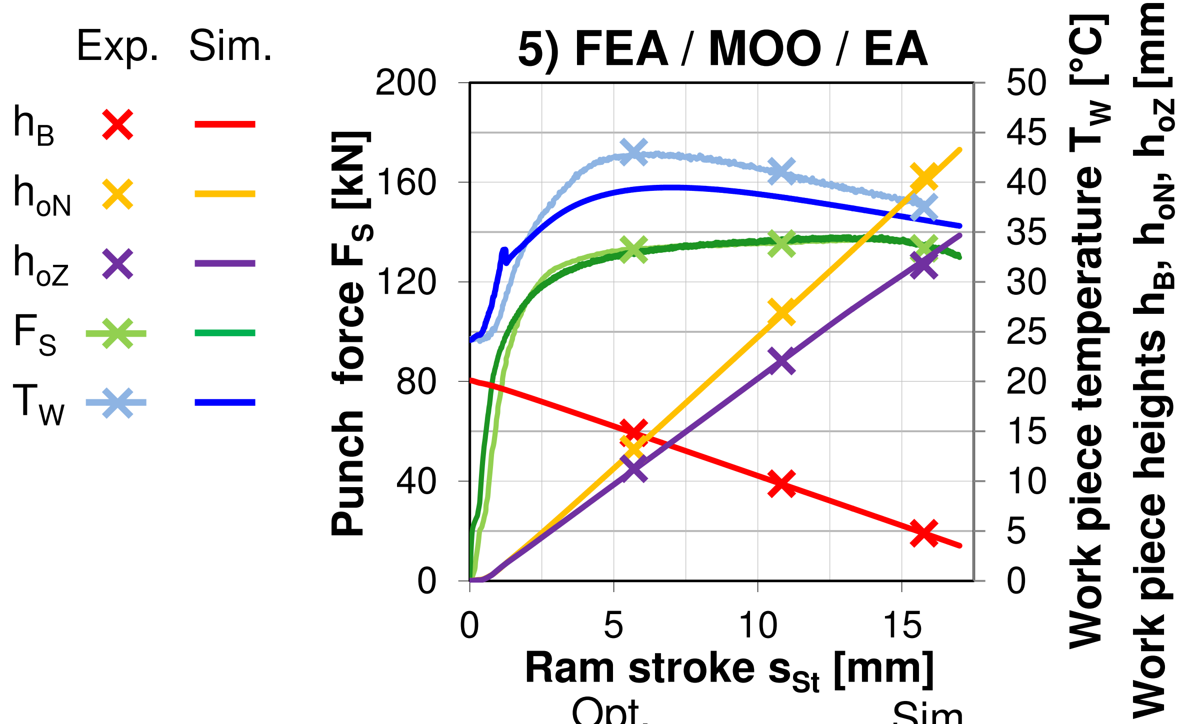


D = 640890 N/mm
μ = 0.023
m = 0.040
α = 68257 W/(m²·K)
V = 0.738

Opt.		Sim.	
Err_h_B	= 0.20	Err_h_B	= 0.20
Err_h_{oN}	= 4.88	Err_h_{oN}	= 4.88
Err_h_{oZ}	= 2.47	Err_h_{oZ}	= 2.47
Err_F_S	= 0.28	Err_F_S	= 0.28
Err_T_W	= 1.44	Err_T_W	= 1.44
Err	**= 9.27**	**Err**	**= 9.27**

	Exp.	Opt.	Sim.
$h_{B,1}$ [mm]	14.82	14.79	14.79
$h_{B,2}$ [mm]	9.74	9.67	9.67
$h_{B,3}$ [mm]	4.74	4.72	4.72
$h_{oN,1}$ [mm]	13.18	13.26	13.26
$h_{oN,2}$ [mm]	26.96	26.87	26.87
$h_{oN,3}$ [mm]	40.56	40.21	40.21
$h_{oZ,1}$ [mm]	11.23	11.06	11.06
$h_{oZ,2}$ [mm]	22.05	21.88	21.88
$h_{oZ,3}$ [mm]	31.65	31.78	31.78
$F_{S,1}$ [kN]	132.9	129.3	129.3
$F_{S,2}$ [kN]	135.3	133.4	133.4
$F_{S,3}$ [kN]	133.4	130.9	130.9
$T_{W,1}$ [°C]	43.0	39.8	39.8
$T_{W,2}$ [°C]	41.1	37.1	37.1
$T_{W,3}$ [°C]	37.5	33.9	33.9

Inverse parameter calibration of FEA settings
FEA / Multi objective optimization / Evolutionary algorithm



	Exp.	Opt.	Sim.
$h_{B,1}$ [mm]	14.82	14.81	14.81
$h_{B,2}$ [mm]	9.74	9.70	9.70
$h_{B,3}$ [mm]	4.74	4.75	4.75
$h_{oN,1}$ [mm]	13.18	13.14	13.14
$h_{oN,2}$ [mm]	26.96	26.68	26.68
$h_{oN,3}$ [mm]	40.56	39.94	39.94
$h_{oZ,1}$ [mm]	11.23	11.15	11.15
$h_{oZ,2}$ [mm]	22.05	22.09	22.09
$h_{oZ,3}$ [mm]	31.65	32.20	32.20
$F_{S,1}$ [kN]	132.9	130.9	130.9
$F_{S,2}$ [kN]	135.3	136.7	136.7
$F_{S,3}$ [kN]	133.4	134.6	134.6
$T_{W,1}$ [°C]	43.0	39.3	39.3
$T_{W,2}$ [°C]	41.1	38.5	38.5
$T_{W,3}$ [°C]	37.5	36.2	36.2

D = 593550 N/mm
μ = 0.022
m = 0.053
α = 29368 W/(m²·K)
V = 0.587

Opt.		Sim.	
Err_h_B	= 0.07	Err_h_B	= 0.07
Err_h_{oN}	= 15.94	Err_h_{oN}	= 15.94
Err_h_{oZ}	= 9.98	Err_h_{oZ}	= 9.98
Err_F_S	= 0.08	Err_F_S	= 0.08
Err_T_W	= 0.82	Err_T_W	= 0.82
Err	**= 26.89**	**Err**	**= 26.89**

Agenda

1. Introduction
2. Experiments on backward-rod-backward-cup-extrusion
3. Sensitivity analysis of FEA simulations of backward-rod-backward-cup-extrusion
4. Inverse parameter calibration of FEA settings and comparison to experimental data
5. Conclusions

Conclusions

- Material flow in combined cold forging processes is influenced by a variety of process parameters
- For automatic process optimisation it is necessary to exactly know which parameters can be used to influence the material flow
- Another requirement for automatic process optimisation is to exactly predict the real material flow by FEA
- Inverse parameter calibration can be used to achieve more proper FEA models or at least more proper FEA model settings
- Results using MOP are not satisfying in the current case
- Parameter calibration using FEA is very time-consuming
- Suitable cascaded procedure should be developed

Thank you for your attention!