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**

10\textsuperscript{th} Weimar Optimization and Stochastic Days 2013

Weimar, November 22\textsuperscript{nd} 2013

Dipl.-Ing. Christian Mletzko
Agenda

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

Improvement of material flow prediction of combined cold forging processes by parameter calibration
Introduction
Problem and objective

Challenge:
Production of the heat dissipator

Requirements: • Combined cold forging process
                   • One forming stage / One stroke
                   • No mechanical stops
Introduction
Procedure during automatic process optimisation

Design
- Optimal Design
- Robust?

Optimisation of objective function(s)
- e.g. minimisation of post chipping treatments

Design n
- Output-Parameter
  - Determination of workpiece geometry

Design n+1
- Input-Parameter
  - e.g. setting of
    - Tool geometry
    - Tribology
    - Tool kinematics

Ideal geometry

Real forming process
- yes
- no

FEA forming simulation

- Ideal process

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

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Improvement of material flow prediction of combined cold forging processes by parameter calibration
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Experiments on backward-rod-backward-cup-extrusion
Process steps

1) Loading

2) Forging

3) Ejecting

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

Load cell
Punch
Die
Counter punch
Punch
Work piece
Die
Experiments on backward-rod-backward-cup-extrusion
Test parameters and output parameters

**Test parameters**
- Material: EN AW 1050A, \( h_0 = 20.105 \text{ mm}, d_0 = 23.905 \text{ mm} \)
- 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 \( T_W \)
Improvement of material flow prediction of combined cold forging processes by parameter calibration

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

Tool scheme

Process data

Work piece

Punch force $F_s$ [kN]

Work piece temperature $T_W$ [°C]

Ram stroke $s_{St}$ [mm]

$s_{St, 1}$ [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
$h_B, 2$ [mm] = 9.74  $h_{oN, 2}$ [mm] = 26.96
$h_B, 3$ [mm] = 4.74  $h_{oN, 3}$ [mm] = 40.56

with $\Delta h_B = 0.1$ mm  with $\Delta h_{oN} = 0.1$ mm

$h_{oN, 1}$ [mm] = 11.23  $h_{oZ, 1}$ [mm] = 11.23
$h_{oN, 2}$ [mm] = 22.05  $h_{oZ, 2}$ [mm] = 22.05
$h_{oN, 3}$ [mm] = 31.65  $h_{oZ, 3}$ [mm] = 31.65

with $\Delta h_{oZ} = 0.1$ mm

$F_{S, 1}$ [kN] = 132.9  $T_{W, 1}$ [°C] = 43.0
$F_{S, 2}$ [kN] = 135.3  $T_{W, 2}$ [°C] = 41.1
$F_{S, 3}$ [kN] = 133.4  $T_{W, 3}$ [°C] = 37.5

with $\Delta F_S = 5$ kN  with $\Delta T_W = 3$ °C
Experiments on backward-rod-backward-cup-extrusion: Experiments vs. FEA simulation

**FEA standard settings**

- D = ∞ N/mm
- μ = 0.03
- m = 0.18
- α = 20000 W/(m²·K)
- V = 0.750

**Work piece heights**

- h_{B,1} [mm] = 14.82
- h_{B,2} [mm] = 9.74
- h_{B,3} [mm] = 4.74
- h_{oN,1} [mm] = 13.18
- h_{oN,2} [mm] = 26.96
- h_{oN,3} [mm] = 40.56
- h_{oZ,1} [mm] = 11.23
- h_{oZ,2} [mm] = 22.05
- h_{oZ,3} [mm] = 31.65

**Punch force**

- F_{S,1} [kN] = 132.9
- F_{S,2} [kN] = 135.3
- F_{S,3} [kN] = 133.4

**Temperature**

- T_{W,1} [°C] = 43.0
- T_{W,2} [°C] = 41.1
- T_{W,3} [°C] = 37.5

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

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Agenda

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

Way of procedure

Parameter

Stiffness
\(D = \begin{cases} 200000 \text{ N/mm} & \text{if } m = 0 \\ 700000 \text{ N/mm} & \text{if } m = 0.3 \end{cases}\)

Friction
\(\mu = \begin{cases} 0.001 & \text{if } \sigma_N < 0.3 \\ 0.15 & \text{if } \sigma_N \geq 0.3 \end{cases}\)

Dissipation
\(\alpha = \begin{cases} 20000 \text{ W/(m}^2\cdot\text{K}) & \text{if } \sigma_N < 0.3 \\ 80000 \text{ W/(m}^2\cdot\text{K}) & \text{if } \sigma_N \geq 0.3 \end{cases}\)

Heat transfer
\(\dot{Q} = \begin{cases} 0.001 & \text{if } T_1 < 0.15 \\ 1 & \text{if } T_1 \geq 0.15 \end{cases}\)

Sensitivity analysis
(DoE and MOP)

Inverse parameter calibration
(MOP and FEA)

Forming experiments

Target function(s)

\(F_S = f(s_{St})\)
\(T_W = f(s_{St})\)
\(h_{oN} = f(s_{St})\)
\(h_{oZ} = f(s_{St})\)
MOP settings: 5 input parameters, 77 support points, 39 test points, $\Delta \text{CoP} = 0.03$

- 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 $\mu$ 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, $\Delta \text{CoP} = 0.03$

- Cup height $h_{oN, i}$ depends mainly on the friction parameters $\mu$ 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 $h_{oN, 3}$

Improvement of material flow prediction of combined cold forging processes by parameter calibration
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**Sensitivity analysis of FEA simulations**

**MOP results: Rod height**

**MOP settings:** 5 input parameters, 77 support points, 39 test points, $\Delta \text{CoP} = 0.03$

- Rod height $h_{oz,i}$ depends on the friction parameters $\mu$ and $m$
- Very good Coefficients of Prognosis
- Strong correlation between $h_{oz,1}$, $h_{oz,2}$ and $h_{oz,3}$
Improvement of material flow prediction of combined cold forging processes by parameter calibration

**Sensitivity analysis of FEA simulations**

**MOP results: Punch force**

**MOP settings:** 5 input parameters, 77 support points, 39 test points, $\Delta \text{CoP} = 0.03$

- Punch force $F_{S,i}$ depends on the friction parameters $\mu$ 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, $\Delta \text{CoP} = 0.03$

- Work piece temperature $T_{w,i}$ depends on the heat transfer coefficients $\alpha$ and friction parameters $\mu$ and $m$
- Very good Coefficients of Prognosis
- Strong correlation between $T_{w,1}$, $T_{w,2}$ and $T_{w,3}$
Agenda

1. Introduction

2. Experiments on backward-rod-backward-cup-extrusion


4. Inverse parameter calibration of FEA settings and comparison to experimental data

5. Conclusions
Inverse parameter calibration of FEA settings
Way of procedure

Parameter

Stiffness

-\[ D = \begin{cases} 350000 \text{ N/mm} \\ 700000 \text{ N/mm} \end{cases} \]

Friction

-\[ m = 0 \]
-\[ \mu = \begin{cases} 0.001 \\ 0.1 \end{cases} \]

Dissipation

-\[ \nu = 0.5 \]
-\[ \alpha = \begin{cases} 20000 \text{ W/(m}^2\cdot\text{K)} \\ 80000 \text{ W/(m}^2\cdot\text{K)} \end{cases} \]

Heat transfer

Forming experiments

Parameter sensitivity analysis (DOE and MOP)

Inverse parameter calibration (MOP and FEA)

Target function(s)

-\[ h_B = f(s_{St}) \]
-\[ h_{ON} = f(s_{St}) \]
-\[ h_{OZ} = f(s_{St}) \]
-\[ F_S = f(s_{St}) \]
-\[ T_W = f(s_{St}) \]
Inverse parameter calibration of FEA settings

Objective functions

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

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

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

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

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

Failure sum: $\text{Err} = \text{Err}_{-h_B} + \text{Err}_{-h_{oN}} + \text{Err}_{-h_{oZ}} + \text{Err}_{-F_S} + \text{Err}_{-T_W}$
Inverse parameter calibration of FEA settings
Conducted variants

Sensitivity analysis
DOE and MOP

Using MOP

Using FEA

MOP / SOO
Genetic algorithm

MOP / SOO
Evolutionary algorithm

MOP / MOO
Evolutionary algorithm

FEA / SOO
Genetic algorithm

FEA / MOO
Evolutionary algorithm

Single objective optimization

Multi objective optimization

Sensitivity analysis
DOE and MOP

Optimization

Using MOP

Using FEA

Single objective optimization

Multi objective optimization

MOP / SOO
Evolutionary algorithm

MOP / MOO
Evolutionary algorithm

FEA / SOO
Genetic algorithm

FEA / MOO
Evolutionary algorithm

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### Inverse parameter calibration of FEA settings

**Input parameters after calibration runs**

<table>
<thead>
<tr>
<th></th>
<th>D [N/mm]</th>
<th>µ [-]</th>
<th>m [-]</th>
<th>α [W/(m²·K)]</th>
<th>V [-]</th>
<th>Err [-]</th>
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<tr>
<td>Evolutionary algorithm</td>
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<td>0.053</td>
<td>29368</td>
<td>0.587</td>
<td>26.89</td>
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</table>
Inverse parameter calibration of FEA settings
MOP / Single objective optimization / Genetic algorithm

1) MOP / SOO / GA

Ram stroke $s_{st}$ [mm] vs. Punch force $F_S$ [kN]

<table>
<thead>
<tr>
<th>h_B</th>
<th>h_on</th>
<th>h_oz</th>
<th>F_S</th>
<th>T_W</th>
</tr>
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<tbody>
<tr>
<td>14.82</td>
<td>14.76</td>
<td>14.77</td>
<td>13.18</td>
<td>13.50</td>
</tr>
<tr>
<td>9.74</td>
<td>9.63</td>
<td>9.66</td>
<td>26.96</td>
<td>27.35</td>
</tr>
<tr>
<td>4.74</td>
<td>4.68</td>
<td>4.71</td>
<td>40.56</td>
<td>41.00</td>
</tr>
<tr>
<td>13.18</td>
<td>13.32</td>
<td>13.50</td>
<td>26.96</td>
<td>27.35</td>
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<tr>
<td>26.96</td>
<td>26.98</td>
<td>27.35</td>
<td>40.56</td>
<td>41.00</td>
</tr>
<tr>
<td>11.23</td>
<td>11.21</td>
<td>10.34</td>
<td>22.05</td>
<td>20.14</td>
</tr>
<tr>
<td>31.65</td>
<td>31.68</td>
<td>28.83</td>
<td>31.65</td>
<td>28.83</td>
</tr>
<tr>
<td>132.9</td>
<td>135.3</td>
<td>133.6</td>
<td>135.3</td>
<td>133.6</td>
</tr>
<tr>
<td>133.4</td>
<td>132.2</td>
<td>130.3</td>
<td>133.4</td>
<td>130.3</td>
</tr>
<tr>
<td>43.0</td>
<td>42.4</td>
<td>36.2</td>
<td>41.1</td>
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<td>41.1</td>
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<td>37.5</td>
<td>33.5</td>
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<tr>
<td>37.5</td>
<td>38.1</td>
<td>33.5</td>
<td>37.5</td>
<td>33.5</td>
</tr>
</tbody>
</table>

Err  = 3.73
Err_h_B = 0.84
Err_h_on = 1.71
Err_h_oz = 0.30
Err_F_S = 0.85
Err_T_W = 0.03

D = 684060 N/mm
$\mu = 0.001$
m = 0.118
$\alpha = 25894 \text{ W/(m}^2\cdot\text{K)}$
$V = 0.500$
Inverse parameter calibration of FEA settings
MOP / Single objective optimization / Evolutionary algorithm

2) MOP / SOO / EA

<table>
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<th>Sim.</th>
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<td>h_B</td>
<td>x</td>
</tr>
<tr>
<td>h_oN</td>
<td>x</td>
</tr>
<tr>
<td>h_oZ</td>
<td>x</td>
</tr>
<tr>
<td>F_S</td>
<td>x</td>
</tr>
<tr>
<td>T_W</td>
<td>x</td>
</tr>
<tr>
<td>h_B, 1 [mm]</td>
<td>14.82</td>
</tr>
<tr>
<td>h_B, 2 [mm]</td>
<td>9.74</td>
</tr>
<tr>
<td>h_B, 3 [mm]</td>
<td>4.74</td>
</tr>
<tr>
<td>h_oN, 1 [mm]</td>
<td>13.18</td>
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<tr>
<td>h_oN, 2 [mm]</td>
<td>26.96</td>
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<tr>
<td>h_oN, 3 [mm]</td>
<td>40.56</td>
</tr>
<tr>
<td>h_oZ, 1 [mm]</td>
<td>11.23</td>
</tr>
<tr>
<td>h_oZ, 2 [mm]</td>
<td>22.05</td>
</tr>
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<td>h_oZ, 3 [mm]</td>
<td>31.65</td>
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<tr>
<td>F_S, 1 [kN]</td>
<td>132.9</td>
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<tr>
<td>F_S, 2 [kN]</td>
<td>135.3</td>
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<td>F_S, 3 [kN]</td>
<td>133.4</td>
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<tr>
<td>T_W, 1 [°C]</td>
<td>43.0</td>
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<td>T_W, 2 [°C]</td>
<td>41.1</td>
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<tr>
<td>T_W, 3 [°C]</td>
<td>37.5</td>
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D = 684420 N/mm
µ = 0.001
m = 0.119
α = 26878 W/(m²·K)
V = 0.500
Inverse parameter calibration of FEA settings
MOP / Multi objective optimization / Evolutionary algorithm

<table>
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<tr>
<th>Experiment</th>
<th>Simulation</th>
<th>Optimum</th>
<th>Simulation</th>
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<tr>
<td>T_W</td>
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<td>26.96</td>
<td>27.10</td>
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\[
\begin{align*}
D &= 547670 \text{ N/mm} \\
\mu &= 0.006 \\
m &= 0.042 \\
\alpha &= 34749 \text{ W/(m}^2\text{·K)} \\
V &= 0.791 \\
\end{align*}
\]

\[
\begin{align*}
\text{Err}_{h_B} &= 0.29 \\
\text{Err}_{h_oN} &= 17.62 \\
\text{Err}_{h_oZ} &= 20.64 \\
\text{Err}_{F_S} &= 0.07 \\
\text{Err}_{T_W} &= 0.04 \\
\text{Err} &= 38.66 \\
\end{align*}
\]
Inverse parameter calibration of FEA settings
FEA / Single objective optimization / Genetic algorithm

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Sim.</th>
</tr>
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<tbody>
<tr>
<td>h_B</td>
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</tr>
<tr>
<td>h_oN</td>
<td></td>
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<tr>
<td>h_oZ</td>
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</tr>
<tr>
<td>F_S</td>
<td></td>
</tr>
<tr>
<td>T_W</td>
<td></td>
</tr>
</tbody>
</table>

4) FEA / SOO / GA

Work piece heights $h_B$, $h_{oN}$, $h_{oZ}$ [mm]

- $h_{B,1}$ [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

Punch force $F_S$ [kN]

- $F_{S,1}$ [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

Work piece temperature $T_W$ [°C]

- $T_{W,1}$ [°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

Work piece heights $h_B$, $h_{oN}$, $h_{oZ}$ [mm]

- $h_{B,1}$ [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

Punch force $F_S$ [kN]

- $F_{S,1}$ [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

Work piece temperature $T_W$ [°C]

- $T_{W,1}$ [°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

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

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Inverse parameter calibration of FEA settings

FEA / Multi objective optimization / Evolutionary algorithm

5) FEA / MOO / EA

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Sim.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_B$</td>
<td>![Blue X]</td>
</tr>
<tr>
<td>$h_{oN}$</td>
<td>![Yellow X]</td>
</tr>
<tr>
<td>$h_{oZ}$</td>
<td>![Purple X]</td>
</tr>
<tr>
<td>$F_S$</td>
<td>![Green X]</td>
</tr>
<tr>
<td>$T_W$</td>
<td>![Blue X]</td>
</tr>
</tbody>
</table>

Punch force $F_S$ [kN]

Ram stroke $s_{St}$ [mm]

| Work piece heights $h_B$, $h_{oN}$, $h_{oZ}$ [mm] |
|------|-----|-----|
| $h_{B,1}$ | 14.82 | 14.81 | 14.81 |
| $h_{B,2}$ | 9.74  | 9.70  | 9.70  |
| $h_{B,3}$ | 4.74  | 4.75  | 4.75  |
| $h_{oN,1}$ | 13.18 | 13.14 | 13.14 |
| $h_{oN,2}$ | 26.96 | 26.68 | 26.68 |
| $h_{oN,3}$ | 40.56 | 39.94 | 39.94 |
| $h_{oZ,1}$ | 11.23 | 11.15 | 11.15 |
| $h_{oZ,2}$ | 22.05 | 22.09 | 22.09 |
| $h_{oZ,3}$ | 31.65 | 32.20 | 32.20 |

| Work piece temperature $T_W$ [°C] |
|------|-----|-----|
| $T_{W,1}$ | 43.0 | 39.3 | 39.3 |
| $T_{W,2}$ | 41.1 | 38.5 | 38.5 |
| $T_{W,3}$ | 37.5 | 36.2 | 36.2 |

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

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Agenda

1. Introduction
2. Experiments on 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!