Optimization of Tooling Design for Hot Mandrel Bending of Pipe Elbows

J. Prehm (DynaWeld GmbH & Co. KG)
U. Diekmann (Matplus GmbH)
W. Homberg, D. Tabakajew (LUF, University of Paderborn)
H. Uysal, N. Schönhoff (Lindemann GmbH & Co.KG)

15. Deutsches LS-DYNA Forum
15. - 17. October 2018 in Bamberg
Introduction
  • What is a Pipe Elbow?
  • How it is made?

Objectives
  • Resource efficiency and productivity
  • New tools for SME

Performed work and selected results
  • FEM Modelling
  • Materials Modelling
  • Meta-Modelling

Summary and Outlook
Elbows from seamless or ERW pipes

Outside diameter: 17.2 - 610.0 mm
Wall thickness: 1.8 - 32.0 mm
Radius: 2D / 3D / 5D

Challenge
• Broad range of dimensions
• Broad range of tools (mandrels)
Production of Elbows by Hot Mandrel Bending

1. (Seamless) Tubes/Pipes are cut to sections
2. Pipe sections are placed on a tool/mandrel
3. Simultaneous inductive heating (~ 800 °C) and forming
4. Forming consists of simultaneous widening and bending
5. Result are elbows showing homogeneous wall thickness (inside and outside)

Challenges:
• Quality, Resource efficiency, Productivity
Objectives

1. Optimization of the process
   • Reduction of material losses
     • starting from 8 – 25%
   • Reduction of energy consumption
   • Decrease of production time
   • Increase in productivity

2. Creation of software tools for SME:
   • Easy to use tools for optimization of processes and tool design
   • Transfer of technology to other SME concerning hot forming
Example MatPlus HQ – shop floor App

FEM- Calculation
Initial Idea - Customize a free 3D FEA System
Initial Idea - Customize a free 3D FEA System

Vision:
Code_Aster as basis for:

- Pre-Configured App
- Easy to use
- No Licensing issues
- No barriers for use in SME

Initial Idea - Customize a free 3D FEA System
Code_Aster seemed to be powerful

..but was finally not suitable for our complex system
  - Contact conditions
  - Damage modeling for hot forming
  - Robustness and performance
Final Workflow of the project

• Determination of boundary conditions
  - Materials properties
  - Friction coefficients
  - Temperature fields

• Generation of automated calculations
  - Pre-Processing including parametric modelling of geometries
  - Batch processing of many calculations (> 2.500)
  - using a multi-processor cluster with LS DYNA
  - Automated post processing of the required features

• Meta-Modelling
  - Evaluate calculations using different methods like neural networks, random forest
  - Optimization runs using meta-models
Calculation of materials properties using JMatPro

Generation of consistent material cards for forming simulations
- Thermo-Physical Properties
- Flow curves
Hot Tensile Testing EN ISO 6892-2

Materials:
P235, 1.4541, 10CrMo9-10

Temperature:
700 °C
900 °C

Strain Rates:
0.1/s, 1/s, 10/s
Simplified Johnson Cock model

\[ \sigma = (A + B \exp(n \varepsilon)) \]

no influence of strain rate and temperature

### Tab. 2 Results of tensile tests, 1.4541

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Temp. °C</th>
<th>D₀ mm</th>
<th>a₀ mm</th>
<th>b₀ mm</th>
<th>a_u mm</th>
<th>b_u mm</th>
<th>L₀ mm</th>
<th>L_U mm</th>
<th>R_p0.2 MPa</th>
<th>R_m MPa</th>
<th>A_g %</th>
<th>A₅ %</th>
<th>Z %</th>
<th>Strain rate 1/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>T 700C 0.1 1</td>
<td>700</td>
<td>89.60</td>
<td>3.15</td>
<td>12.50</td>
<td>0.69</td>
<td>9.08</td>
<td>10.00</td>
<td>15.82</td>
<td>130.2</td>
<td>298.7</td>
<td>29.5</td>
<td>58.2</td>
<td>84.1</td>
<td>0.1</td>
</tr>
<tr>
<td>T 700C 0.1 2</td>
<td>700</td>
<td>89.60</td>
<td>3.15</td>
<td>12.50</td>
<td>0.64</td>
<td>8.94</td>
<td>10.00</td>
<td>16.36</td>
<td>140.9</td>
<td>296.4</td>
<td>29.6</td>
<td>63.6</td>
<td>85.5</td>
<td>0.1</td>
</tr>
<tr>
<td>T 700C 0.1 3</td>
<td>700</td>
<td>89.60</td>
<td>3.15</td>
<td>12.50</td>
<td>0.74</td>
<td>9.05</td>
<td>10.00</td>
<td>16.29</td>
<td>157.0</td>
<td>298.6</td>
<td>30.5</td>
<td>62.9</td>
<td>83.1</td>
<td>0.1</td>
</tr>
<tr>
<td>average</td>
<td>700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>142.7</td>
<td>297.9</td>
<td>29.9</td>
<td>61.6</td>
<td>84.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### Tab. 3 Results of tensile tests, P235

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Temp. °C</th>
<th>D₀ mm</th>
<th>a₀ mm</th>
<th>b₀ mm</th>
<th>a_u mm</th>
<th>b_u mm</th>
<th>L₀ mm</th>
<th>L_U mm</th>
<th>R_p0.2 MPa</th>
<th>R_m MPa</th>
<th>A_g %</th>
<th>A₅ %</th>
<th>Z %</th>
<th>Strain rate 1/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>T 700C 0.1 1</td>
<td>700</td>
<td>82.50</td>
<td>3.81</td>
<td>12.50</td>
<td>0.17</td>
<td>5.40</td>
<td>10.00</td>
<td>21.61</td>
<td>73.7</td>
<td>117.7</td>
<td>21.5</td>
<td>116.1</td>
<td>98.1</td>
<td>0.1</td>
</tr>
<tr>
<td>T 700C 0.1 2</td>
<td>700</td>
<td>82.50</td>
<td>3.81</td>
<td>12.50</td>
<td>0.15</td>
<td>5.38</td>
<td>10.00</td>
<td>21.88</td>
<td>80.3</td>
<td>120.8</td>
<td>17.7</td>
<td>118.8</td>
<td>98.3</td>
<td>0.1</td>
</tr>
<tr>
<td>T 700C 0.1 3</td>
<td>700</td>
<td>82.50</td>
<td>3.81</td>
<td>12.50</td>
<td>0.14</td>
<td>5.53</td>
<td>10.00</td>
<td>21.11</td>
<td>75.6</td>
<td>118.0</td>
<td>19.6</td>
<td>111.1</td>
<td>98.4</td>
<td>0.1</td>
</tr>
<tr>
<td>average</td>
<td>700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>76.5</td>
<td>118.8</td>
<td>19.6</td>
<td>115.3</td>
<td>98.3</td>
<td>0.1</td>
</tr>
</tbody>
</table>

\[ \varepsilon_{fail} = \ln \frac{100}{100-Z} \]

P235: \( \varepsilon_{fail} = 4.07 \)

1.4541: \( \varepsilon_{fail} = 1.83 \)
Parameters/Variation of Tool Geometry

- Angle $\alpha$
- Angle $\beta$
- Tube diameter
- Height of mandrel
- Bending radius
- Mandrel diameter
- Length of mandrel
Tool for automatic generation of Input-Files
App for Parametric Design of Mandrel Geometry

Fixed parameters for a certain dimension
parameters for optimization can be processed in batch mode
>2500 Calculations using LS-DYNA

- 8 from ~1000 dimensions of elbows
- Variation of parameters (material, radius, diameter, wall thickness, length, height, angle, expansion)

Computation time using an 8 Core, CPU: Intel Xeon E5-2670

- 456 days, 14 hours, 20 minutes
- was reduced by using a bigger university cluster
Influence of Expansion Ratio on Angle in Tolerance

114.3 x 3.6 (Norm 3) from 82.5 x 3.6
Influence of Expansion Ratio on Plastic strain

114.3 x 3.6 (Norm 3) from 82.5 x 3.6

max Plastic Strain vs. Expansion Ratio [％]
Meta-Modelling for Multi-Variate Optimization

- x.000 FEM Calculations
- Data Analysis and Modelling
  - Statistics
  - Regression
  - Black Box (Neural Networks, Random Forrest)
- Optimisation
  (and final FEM for Verification)
Random Forest Workspace:

Here: model for variation of wall thickness

Input parameters:
- Tool lengths
- Tool height
- Expansion angle
Combination of all models to optimize the target values:
Combination of all models to optimize the target values:

Delta wall thickness
Combination of all models to optimize the target values:

Delta wall thickness

Delta outer diameter
Combination of all models to optimize the target values:

- Delta wall thickness
- Delta outer diameter
- max. angle in norm
Results of a meta-model:

<table>
<thead>
<tr>
<th>Best Value</th>
<th>Tool angle_const [°]</th>
<th>Tool height [mm]</th>
<th>Tool_length [mm]</th>
<th>Objective value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>205.6</td>
<td>224.55</td>
<td>0.24160192</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>205.6</td>
<td>230.05</td>
<td>0.241961948</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>206.15</td>
<td>224.55</td>
<td>0.242608664</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>206.15</td>
<td>230.05</td>
<td>0.242728537</td>
</tr>
<tr>
<td>5</td>
<td>57.75</td>
<td>205.6</td>
<td>224.55</td>
<td>0.247997124</td>
</tr>
<tr>
<td>6</td>
<td>57.75</td>
<td>205.6</td>
<td>230.05</td>
<td>0.249123411</td>
</tr>
<tr>
<td>7</td>
<td>57.75</td>
<td>206.15</td>
<td>224.55</td>
<td>0.249582874</td>
</tr>
<tr>
<td>8</td>
<td>57.75</td>
<td>206.15</td>
<td>230.05</td>
<td>0.250483848</td>
</tr>
<tr>
<td>9</td>
<td>55.5</td>
<td>205.6</td>
<td>230.05</td>
<td>0.258777058</td>
</tr>
<tr>
<td>10</td>
<td>55.5</td>
<td>205.6</td>
<td>224.55</td>
<td>0.258832455</td>
</tr>
</tbody>
</table>

Good agreement with FEM calculation
Verification

Production of elbows with optimized tool
• Higher production yield: + 14%
• Higher production speed: + x
Damage by unstable process
Summary and Results

New tooling design leads to:

- Increased materials efficiency: Losses can be reduced significantly
- Increased productivity: Production speed can be increased significantly
- Increased energy efficiency by higher speed of production and less material
- Findings were validated in practical tests at Lindemann—but not yet in industrial production

New software and tools help to reduce complexity:

- easy to use
- to automatically perform many calculations
- Meta-modelling can be used for optimisation, saves time and reduces number of FE-computations

Software will be further developed to help other SME improving their production processes