CLOSED LOOP CONTROL OF THE 
3D BENDING PROCESS

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1. INTRODUCTION
Modern metal-forming processes have two very demanding goals:

• to produce net shape components
• to assure stable zero-defect production
The metal-forming system consists of several influential parameters, the most important are:

- incoming material
- tools
- the forming machine
- tribology
- the forming process itself.

These parameters are in close correlation, resulting in a highly non-linear thermo-elastoplastic problem.
Correlation between the part width and the flow stress of wire.

how to assure zero defect production?

- to narrow tolerances of the process parameters
- to redesign the process by repositioning it into stable technological windows
- to implement closed loop control

but:
prior taking decisions to make cost evaluation
The paper presents the possibility to control the mechanical properties of the wire material, since it was experimentally verified that they are the most important for a stable shape of 3D bent products.
2. PRELIMINARY INVESTIGATIONS
3D bent product and its width fluctuation.

\[ b_{rel} = \frac{b(l) - b_{min}}{b_{max} - b_{min}} \]

Correlation between the part width and the flow stress of wire.

\[ Y_{rel} = \frac{Y(l) - Y_{min}}{Y_{max} - Y_{min}} \]
3. MATHEMATICAL MODEL OF THE STABILIZATION ALGORITHM
**Schematical representation of the wire straightener in one plane.**

\[ k_i = \left. \frac{d^2 x}{dz^2} \right|_{i} = \frac{1}{r_i} \]

\[ k_{TOT} = \sum_{i=2}^{n-1} |k_i| \]

- **\( k_i \)** - wire curvature at roller \( i \)
- **\( k_{TOT} \)** - total wire curvature
Flow stresses (obtained by tensile tests on wires straightened by different roller presettings) for two different wire qualities in dependence to different total cyclic deformations.
Basic idea

Low carbon cold drawn wire material normally exhibits cyclic softening when being exposed to alternating plastic deformation [Huml], if the total amount of cyclic deformation $kTOT$ is high, the material can harden again.

It can be concluded that the softening or hardening depends on the material and the amount of reversed plastic deformation ($kTOT$). By controlling it, it would be possible to control the flow stress of wire coming out of the straightener.
Numerical model of the wire straightener can be expressed by the functions \( f \) and \( v \), which are the core of the stabilization algorithm:

\[
(F_i, k_{\text{fin}}) = f(d_x, d_y, E, Y, n', K, D_{\text{cyc}}, k_{\text{ini}}, k_i)
\]

\[
x_i = v(k_i)
\]
Measured values and explanation of the stabilization procedure.

3. MATHEMATICAL MODEL OF THE STABILIZATION ALGORITHM
Schematic representation of the stabilization algorithm.
4. MODEL EVALUATION
Experimental equipment in the production

Wire bending machine equipped with the experimental wire straightener

Courtesy of NIKO, 2000
Laser measuring head for on-line control of wire diameter

Basic characteristics:

- Range 0.1 – 10 mm
- Resolution: 0.1μm
- Repeatability: 0.3 μm
- Measuring field: 13X13
New and old roller positions

<table>
<thead>
<tr>
<th>roller no. i</th>
<th>$X_{i,1}$</th>
<th>$X_{i,2}$</th>
<th>$\Delta X_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 3, 5, 7</td>
<td>0 mm</td>
<td>0 mm</td>
<td>0 mm</td>
</tr>
<tr>
<td>2</td>
<td>0.19 mm</td>
<td>0.17 mm</td>
<td>-0.02 mm</td>
</tr>
<tr>
<td>4</td>
<td>0.17 mm</td>
<td>0.22 mm</td>
<td>0.05 mm</td>
</tr>
<tr>
<td>6</td>
<td>0.53 mm</td>
<td>0.61 mm</td>
<td>0.08 mm</td>
</tr>
</tbody>
</table>
Experimental evaluation of the proposed model:
A - wire path, B - product geometry (width b - Figure 1), before (jth interval) and after presetting (j+1st interval) of the rollers.
5. FEED BACK SYSTEM
Schematic representation of the close loop control system for a two plane roller straightener.
6. CONCLUSIONS
Closed loop control of the 3D bending process is possible when

- affecting the mechanical properties of the incoming material by roller straighteners
- using process stabilisation algorithm
- from force measurements to flow stresses determination and then to reposition of rollers
Benefits

- it is not necessary to narrow the mechanical properties of the incoming material (which is expensive)
- the method can be used not only for wire but also for sheet metal
Elements of wire bending force calculation for cyclic loading

\[ Y \neq \text{const.} \]

\[ Y_i = Y_0 \cdot D_{\text{cyc.}}^{i-1} \]

\[
\sigma = E \cdot \varepsilon \\
\frac{d\sigma}{C} = E \left[ 1 - \frac{1}{Y^n} \left( \frac{1}{1+k} \right) \left( \frac{\sigma - E \cdot \varepsilon}{1+k} \right)^n \right] d\varepsilon
\]

\[ C \geq 0 \]

\[ C \leq 0 \]

\[ Y_i = (l) = f^{-1}(F_i(l)) \]