RELIABLE AND FAST PRODUCTION OF SHEET METAL COMPONENTS

Slovenian experiences

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Structure

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3. Incremental forming at SQP in the car business
4. Individual incremental forming of construction elements
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6. Conclusion
1. Introduction

1991:
• Slovenia became an independent country
• Slovenia lost the major portion of its markets in the former Yugoslavia, Soviet Union and CEEC

2000:
• First Slovene tool making company promoted from tool deliverer to developing partner for German car producers

2010:
• Toolmakers now export nearly 60% of their tools to the EU
• Considering that majority of components done in Slovenia for EU car makers are produced with Slovene tools, the total export can be estimated with 90%
Slovenian tool makers are confronted with new challenges:

- parts to be formed are becoming more and more complex
- new materials and technologies are implemented or replaced (metals by polymers, steel alloys by other metallic alloys, single blanks by tailored blanks, hydroforming…)
- increased demand for the reduction of product development time
- increasing number of variants
- shortening of product lifetime
Toolmaking become one of the Slovene strategic orientations

Majority of tool making companies were SMEs, they knew that:
• knowledge and CA tools are precondition for their survival
• because of costs connected they could not effort it
• bridge between academia and tool makers is needed

1994:
TECOS – Slovene Tool and Die Development Centre, a supporting non profit organisation
2. Fast small quantity production of sheet metal components for the car industry
Problems “or” opportunities in car production:

• to reduce the development time and costs, tests will be transferred into the computer supported virtual environment,

• parallelly to these trends industry will still demand (during the product development phase) small quantities of materialised parts with the same performances as ones manufactured later under conditions of mass production,

• implementation of fast and small quantity production (SQP) requires a new way of thinking,

• SQP – a chance for Slovenian tool makers ??!!
E-networking for sheet-metal-forming process evaluation and tool production

[Diagram showing the flow of information between customer, tool factory, University of Ljubljana, and TECOS]
Implementation of CAx tools: Precondition for successful SQP of sheet metal components

Virtual deep drawing process evaluation can be used for:

- determination of the optimal initial blank shape
- evaluation of different forming steps and their optimisation
- prediction of tearing
- prediction of thickness distribution
- evaluation of tool loads
- process evaluation in terms of its stability and safety
Sheet metal formability data evaluation

(University of Ljubljana)

\[
\begin{array}{|c|c|c|c|}
\hline
\alpha & 0 & 45 & 90 \\
\hline
n & 0.163 & 0.156 & 0.141 \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|c|c|}
\hline
C (N/mm^2) & 1311.4 & 1277, \ 2 & 1249,3 \\
\hline
R_p (N/mm^2) & 468,2 & 478,2 & 537,4 \\
\hline
R_m (N/mm^2) & 825,3 & 818,4 & 821,2 \\
\hline
R_p/R_m & 0.568 & 0.583 & 0.654 \\
\hline
A_g (%) & 34.3 & 29.4 & 27.3 \\
\hline
r_{10} & 0.71 & 0.93 & 0.85 \\
\hline
r_{20} & 0.43 & 0.72 & 0.64 \\
\hline
P & 0.340 & 0.381 & 0.346 \\
\hline
\end{array}
\]

\[
\begin{align*}
\bar{r} &= \frac{1}{4} (r_0 + 2r_{45} + r_{90}) \\
\Delta r &= \frac{1}{2} (r_0 - 2r_{45} + r_{90}) \\
\bar{n} &= \frac{1}{4} (n_0 + 2n_{45} + n_{90}) \\
\Delta n &= \frac{1}{2} (n_0 - 2n_{45} + n_{90}) \\
\end{align*}
\]

\[
\begin{array}{|c|c|c|c|c|}
\hline
\bar{r} & \Delta r & \bar{n} & \Delta n & P \\
\hline
0.8554 & 0.9943 & 0.1542 & 0.1453 & 0.3628 \\
\hline
\end{array}
\]
Sheet metal formability data evaluation

(University of Ljubljana)
Combined computer, laser and mechanical support for the fast development and manufacture of sheet-metal forming technologies and tools.
A reverse-engineering procedure for the correction of sheet-metal forming tools

a) original tool,

b) digitised model,

c) hybrid model with a smooth transition of created surfaces to the original STL mesh
3. Incremental forming at SQP in the car business
Differences between mass production and small quantity of sheet metal components

Transfer tooling system

Autonomous sequences
Single point incremental forming - SPIF

The shape of the product is defined by the processor of the machine and no more with the tool!
Assumptions:
1. Plane strain state
2. Isotropic material behaviour
3. Uniform stretching

Analytical modelling of SPIF

First step:
\[ l_1^i = x_{RT}^i \]
\[ l_2^i = \rho_{RT} \cdot \alpha^i \]

\[ l_3^i = \frac{p_z}{\cos \alpha} + \rho_{FP} \cdot \alpha^i - \frac{\rho_{RT} \cdot \sin \alpha^i}{\cos \alpha} - \frac{\rho_{FP} \cdot \sin \alpha^i}{\cos \alpha} \]

\[ \varphi_x^i = \ln \left[ \frac{l_2^i}{l_3^i - l_1^i} \right] \]
\[ \varphi_x^i = \ln \left( \frac{l^i}{l^i_{i-1}} \right) \]
\[ \varphi_y^i = \ln \left[ \frac{\Delta l_{1}^i + \Delta l_{3}^i}{\Delta l_{2}^i} \right] \]

Additional steps:
\[ l_1^{i+1} = l_1^i - \Delta x \quad i = 1 : n \]

\[ l_2^{i+1} = \rho_{RT} \cdot \sin^{-1} \left( \frac{\rho_{RT} + \rho_{FP}}{\sqrt{(p_z^{i+1})^2 + (p_z^{-1})^2}} \right) - \tan^{-1} \left( \frac{p_z^{i+1}}{p_x^i} \right) \]

\[ l_3^{i+1} = \frac{p_z^{i+1}}{\cos \alpha^{i+1}} + \rho_{FP} \cdot \alpha^{i+1} - \frac{\rho_{RT} \cdot \sin \alpha^{i+1}}{\cos \alpha^{i+1}} - \frac{\rho_{FP} \cdot \sin \alpha^{i+1}}{\cos \alpha^{i+1}} \]

ASSUMPTIONS:
1. Plane strain state
2. Isotropic material behaviour
3. Uniform stretching
Analytical modelling of SPIF

\[ T = \tilde{n} \sigma \times dA \]

for \( i \)-th cycle

\[ i^i = t_0 \cdot e^{\varphi_i} = t_0 \cdot e^{-\varphi_i} \]

\[ A_i \approx 2 \cdot i^i \cdot \left[ \sqrt{R_{RT}^2 - (R_{RT} - \Delta z)^2} + i^i \right] \]

\[ F_i = 2 \left( \frac{2}{\sqrt{3}} \right)^n \left( \frac{t_0 \cdot e^{\varphi_i}}{2} \right) t_0 \cdot C \cdot (\varphi_i)^n \cdot e^{\varphi_i} \cdot \sin \alpha \]
From academic research to the industrial application with **BIF - Backward Incremental Forming**

**Stage 1**

**Stage 2**

*How to form neck on thin ball with classical technologies*
Preliminary experimental work

$LFR = \frac{d_p}{d_0}$

$LFR \ldots$ limit forming ratio

$d_p \ldots$ final diameter

$d_0 \ldots$ initial hole

Due to the incremental deformation higher limit forming ratio can be achieved in contrast to classical neck drawing!
New challenge and motivation for 2010!

To form necks in the perpendicular direction to the forming press movement!
4. Individual incremental forming of construction elements
Incremental forming of multi-layer elements - IMLF

multi-layer elements
(up to twelve meters long
and over one meter wide)
Product requirements – STANDARDS (I)

ANTICORROSION STANDARDS (humidity chamber EN 6270 – 2:2005, salt chamber EN 9227:2006 and tropic box)

Findings:
- Majority of specimens exceed requirements.
- Formed area can be treated in the same way as the rest of the surface.
Product requirements – STANDARDS (II)

CONSTRUCTION LOAD CAPACITY STANDARD (four-point bending test)

RESULTS

Load capacity of the multi-layer element can decrease but also highly increase – depends on the design to be formed.
Advantage for customer

Designs offer identification and individuality with minimal costs!

**QUICK AND EFFECTIVE DESIGN**

"puzzle"

- alphabet
- sentences
- ...poetry

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Single Point Incremental Sheet Metal Forming of Facade Elements.
Technology Developed at University of Ljubljana by prof. Kuzman, dr. Petek and implemented in Trimo Trebnje by dr. Zaletelj

ArtMe is the latest, unique, high-tech facade surface treatment that allows literally unlimited shapes, patterns and visual effects to be expressed on the facade for dramatic, individual and creative results.

www.trimo.si

Expression - The game of
- SCALE (abstractness close by pattern distantly)
- SIZE (panel / building envelope)
- SHADOW (depth: 2D pattern → 3D effect)
ArtMe in the UK

The Jodrell Bank Centre for Astrophysics, home to the famous Lovell Telescope, is the UK’s national radio astronomy facility. The Centre is a World leader in radio-astronomy-related, research and technology development, as well as carrying out research across the electromagnetic spectrum, and other theoretical topics. As part of an exciting refurbishment, Trimo’s award-winning, ArtMe, is being used on the facility.

http://www.jb.man.ac.uk/visitorcentre
ArtMe Applications at Public Institutions

East Blackburn Learning Community - UK

Multy Purpose Sport Hall – Mokronog Slovenia

www.trim.co.si

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Forming Laboratory
5. Virtual process optimisation and stability control

- before taking final decisions,
- before starting the tool production,
- when ranking parameters with accordance to their impacts to the process,
- for positioning processes into stable technological windows,
 Optimization of stamping processes
Part and forming sequences

Two main input parameters which could be optimized during development of forming procedure were:

1. the initial shape of the blank (size of the cut-out produced in stage 1, defined by parameter $a$)
2. properties of drawbead (restraining force $F_{db}$).

Remark: for SQP stages 1, 3, 4 will be done by laser.
Expected scatter of input parameters

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Mean value and expected scatter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial sheet thickness</td>
<td>$s_0 = 0.7 \pm 0.05$ (mm)</td>
</tr>
<tr>
<td>Yield stress</td>
<td>$R_p = 152 \pm 45$ (MPa)</td>
</tr>
<tr>
<td>Hardening coefficient</td>
<td>$C = 373 \pm 50$ (MPa)</td>
</tr>
<tr>
<td>Hardening exponent</td>
<td>$n = 0.218 \pm 0.036$ (1)</td>
</tr>
<tr>
<td>Orthogonal coefficient of anisotropy</td>
<td>$\bar{r} = 2.12 \pm 0.2$ (1)</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>$\mu = 0.1 \pm 0.015$ (1)</td>
</tr>
</tbody>
</table>

Where $C$ and $n$ are used in hardening law $\sigma_f = C \cdot \varphi^n$

Assumption: Normal distribution of all input parameters
FE simulations

SOFTWARE:
PAMSTAMP 2G V2004.0

TOOL:
PERFECTLY RIGID

BLANK:
ELASTO-PLASTIC CONSTITUTIVE LAW
KRUPKOWSKI HARDENING LAW WAS USED

FRICTION:
COULOMB’S LAW, \( \mu = 0.1 \)
Technological window for studied process

![Technological window graph](image)

- **CUT-OUT a (mm)**
  - 0 to 90
- **DRAWBEAD FORCE F_{db} (kN/mm)**
  - 0 to 0.08

**Areas:​**
- **WRINKLING**
- **ACCEPTABLE PRODUCTS**
- **LOCALIZATION & FRACTURE**
- **EXCESSIVE THINNING**

**Optimal Setting?**
Response surface methodology - DOE

Danger of localization: \[ D_L = \frac{\varepsilon}{\varepsilon_{FLD}} \]

Danger of extensive thinning: \[ D_T = \frac{s_0 - s}{s_0 - s_{\text{min}}} \]

Danger of wrinkling: \[ D_W = \frac{h_w}{h_w_{\text{max}}} \]

\[ s_{\text{min}} = 0.8 \text{ mm} ; h_{w_{\text{max}}} = 0.08 \text{mm} \]

\[ D (F_{bh}) = \max (D_L, D_T, D_W) < 1 \]

Selected response function:
\[ D_i = \beta_{0i} + \sum_{j=1}^{k} \beta_{ji} \cdot x_j + \sum_{j=1}^{k} \beta_{jji} \cdot x_j^2 + \sum_{j<m=2}^{k} \beta_{jmi} \cdot x_j \cdot x_m \]

Box-Behnken design of experiments (47 experiment)

<table>
<thead>
<tr>
<th>( F_{db} )</th>
<th>( a )</th>
<th>( s )</th>
<th>( R_p )</th>
<th>( C )</th>
<th>( n )</th>
<th>( r )</th>
<th>( \mu )</th>
<th>( D_L )</th>
<th>( D_T )</th>
<th>( D_W )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0</td>
<td>0.75</td>
<td>180</td>
<td>415</td>
<td>0.188</td>
<td>1.92</td>
<td>0.13</td>
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<td>0.96</td>
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<td>120</td>
<td>415</td>
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<tr>
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<td>2.26</td>
<td>2.20</td>
<td>0.01</td>
</tr>
</tbody>
</table>
RSM – Response functions

\[
\ln D_L = -32.064 + 111.136 \cdot F_{db} - 0.240 \cdot a - 79.673 \cdot s - 0.301 \cdot R_p + 0.147 \cdot C
\]

\[
- 334.126 \cdot n + 76.087 \cdot r + 215.998 \cdot \mu + 942.625 \cdot F_{db}^2 - 5.203 \cdot 10^{-5} \cdot E \cdot a^2 - 14.662 \cdot s^2
\]

\[
+ 2.306 \cdot 10^{-5} \cdot R_p^2 + 3.185 \cdot 10^{-6} \cdot C^2 + 28.484 \cdot n^2 - 0.209 \cdot r^2 - 148.556 \cdot \mu^2 \cdot 0.230 \cdot F_{db} \cdot a
\]

\[
+ 123.445 \cdot F_{db} \cdot s - 0.338 \cdot F_{db} \cdot R_p - 0.049 \cdot F_{db} \cdot C + 115.446 \cdot F_{db} \cdot n - 82.454 \cdot F_{db} \cdot r
\]

\[
- 186.487 \cdot F_{db} \cdot \mu + 0.160 \cdot a \cdot s + 1.645 \cdot 10^{-4} \cdot a \cdot R_p - 1.967 \cdot 10^{-4} \cdot a \cdot C + 0.101 \cdot a \cdot n
\]

\[
\ln D_T = -32.064 + 111.136 \cdot F_{db} - 0.240 \cdot a - 79.673 \cdot s - 0.301 \cdot R_p + 0.147 \cdot C
\]

\[
- 334.126 \cdot n + 76.087 \cdot r + 215.998 \cdot \mu + 942.625 \cdot F_{db}^2 - 5.203 \cdot 10^{-5} \cdot E \cdot a^2 - 14.662 \cdot s^2
\]

\[
+ 2.306 \cdot 10^{-5} \cdot R_p^2 + 3.185 \cdot 10^{-6} \cdot C^2 + 28.484 \cdot n^2 - 0.209 \cdot r^2 - 148.556 \cdot \mu^2 \cdot 0.230 \cdot F_{db} \cdot a
\]

\[
+ 123.445 \cdot F_{db} \cdot s - 0.338 \cdot F_{db} \cdot R_p - 0.049 \cdot F_{db} \cdot C + 115.446 \cdot F_{db} \cdot n - 82.454 \cdot F_{db} \cdot r
\]

\[
- 186.487 \cdot F_{db} \cdot \mu + 0.160 \cdot a \cdot s + 1.645 \cdot 10^{-4} \cdot a \cdot R_p - 1.967 \cdot 10^{-4} \cdot a \cdot C + 0.101 \cdot a \cdot n
\]

\[
\ln D_w = -32.064 + 111.136 \cdot F_{db} - 0.240 \cdot a - 79.673 \cdot s - 0.301 \cdot R_p + 0.147 \cdot C
\]

\[
- 334.126 \cdot n + 76.087 \cdot r + 215.998 \cdot \mu + 942.625 \cdot F_{db}^2 - 5.203 \cdot 10^{-5} \cdot E \cdot a^2 - 14.662 \cdot s^2
\]

\[
+ 2.306 \cdot 10^{-5} \cdot R_p^2 + 3.185 \cdot 10^{-6} \cdot C^2 + 28.484 \cdot n^2 - 0.209 \cdot r^2 - 148.556 \cdot \mu^2 \cdot 0.230 \cdot F_{db} \cdot a
\]

\[
+ 123.445 \cdot F_{db} \cdot s - 0.338 \cdot F_{db} \cdot R_p - 0.049 \cdot F_{db} \cdot C + 115.446 \cdot F_{db} \cdot n - 82.454 \cdot F_{db} \cdot r
\]

\[
- 186.487 \cdot F_{db} \cdot \mu + 0.160 \cdot a \cdot s + 1.645 \cdot 10^{-4} \cdot a \cdot R_p - 1.967 \cdot 10^{-4} \cdot a \cdot C + 0.101 \cdot a \cdot n
\]
Results of the optimization procedure

**THEORY:** $F_{db}=0.04\text{kN/mm}, a=70\text{mm}$

**PRACTICE:** $F_{db}=0.04\text{kN/mm}, a=90\text{mm}$

**PRODUCED GEOMETRY OF THE DRAWBEAD**

- 3.97
- 2.28
Sensitivity chart for predicted stability

- Initial sheet thickness $s_0$: 6.13%
- Yield stress $R_p$: 9.85%
- Hardening coefficient $C$: 63.89%
- Hardening exponent $n$: 5.91%
- Orthogonal coefficient of anisotropy $\bar{r}$: 8.53%
- Coefficient of friction $\mu$: 5.69%
6. Conclusion as a vision of Slovene tool making sector

Small quantity or individual production of sheet metal components can be used in a very broad field of application as:

- transportation (street, railway, water, air, space,)
- construction, art, science, medicine, sport, ....

Precondition for fast reactions to market demands:

- Knowledge & experience
- Real & virtual experiments

Redefinition of the term “forming tools”:

Modern forming tools can be defined as mechatronic production subsystems because they contain control and actuating elements, they are in a real time connected to the control units of an integral production system.