Study of Different Plug Geometries and Optimization of Wall Thickness Distribution of a Typical 16-Once Container made in PET
1. Project description
   • Some previous works done on different products
2. How and why that project did start?
3. Basic theory behind the simulations
4. Inputs required
5. End results of 8 different simulations
6. Benefits of using dedicated software to simulate process and get adequate WTD
1. Project description

Main objectives:

• Obtain an *optimized and adequate* wall thickness distribution (WTD) at specific sections of the container

• Use *lowest sheet gage possible* and still meet customers QC requirements to reduce raw material costs

• And validate if a *dedicated software* can be of a certain help
The Product and the process info

- Container size:
  - 16 on. for Guacamole (5.5" X 5.5" X 1.5") (13.5 g / 0.48 oz.)

- Material:
  - Thin gage aPET sheet 23 mils (585 mm) + tie layer and 1 mil PE

- Mold: Machined Aluminum, 6 cavities
- Plug assisted system (syntactic foam)
- Thermoforming machine used: GN 1914DM
- Cycle time: approx. 2.1 sec (28 cycles per minute)
- Molder: Inopak, Division of Cascades LLC., QC, Canada
Optimizing Plug Assist Geometry Using Simulations

Jerry Dees
Engineering Simulations LLC

Existing
Minimum thickness = 0.124 mm

Optimized
Minimum thickness = 0.216 mm
Save 40% on material
Managing Wall Thickness Variation in Thermoformed Parts

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Illustrative Example: PP cup

1. Plug material
2. Surface roughness
3. Plug diameter
4. Plug taper
5. Plug top radius
6. Plug depth
7. Sheet temperature
Similar works done by others and some statistical results
Similar works done by others and some costs perspective

- Cavity (~75%) = 2.2%
- Tooling
- Energy
- Labor (~75%) = 0.6%
- Labor cost
- Mat’l (~25%) = 0.2%
- Plugs (~25%) = 0.8%
- Machine based cost (amortization, space)
- Plastic Material
2. How and why such research project starts?

From previous collaborations with this company

- After 2 Taguchi DoE
  - Taguchi is an old method to minimize *loss* due to not meeting specifications

Vs
• Identify which **process variables** are the most sensitive on ‘**wall thickness distribution**’ (WTD) (the **loss**) and **how to improve output**?
  
  • 1\textsuperscript{st} : 7 variables, 2 conditions, **8 experiments**
  • 2\textsuperscript{nd} : 4 variables, 3 conditions, **9 experiments**
    
    • Oven temp
    • Forming time
    • Plug lowering time
    • Plug velocity

• Result: potential gain of 0.1 sec on cycle time (5 % potential gain in production)
In fact, gains for the thermoformer were:

1. **Better understanding on the sheet behavior during the pre-stretching** due to:
   - The Plug displacement (approx. 2.5 in.)
   - Under a certain Plug velocity (in less than 0.1 sec)

2. **Combined on SPC, a better control on the process and the AQL output**

3. **Opening to a greater technical (and scientific) collaboration**
3. Basic theory around thermoforming

- Type of mold

- Instant Heat transfer sheet and plug or mold
  - Different material stretching rate as per temperature of sheet sections

- Plug material (Al, Syntactic Foam, Nylons, Delrin, ....)
  - Operating *building up* temperature
  - Coefficient of friction (slip)
    - very low slip
    - low slip conditions
From Coulomb’s law, CoF varies with:

- Material combination
- Plug material
- Temperature of plug and sheet
- Nature of surface,
- ...

![Slip (μ[-]) Plot](image.png)

Foam plug

115 °F

130-185 °F
Steps in roll-feed thermoforming

1. **Sheet reheating**
   - Sheet transport in oven by stroke (under a traveling speed)
   - Sheet transfer in ‘forming station’

2. **Pre-stretch**
   - Plug velocity and displacement
   - Mold displacement

3. **Stretch (and forming)**
   - By vacuum and/or pressure

4. **Cooling (final forming)**
   - In-Mold and Outside-Mold contact

5. **Die-cutting**
Process modelisation (use of a dedicated software)

- Process modelisation involves:
  1. Complicated mathematical equations
     - Thermal
     - Mechanical
     - Rheology
     - Thermo-mechanical behavior
     - ...
  2. FEM methodology using different models:
     - 2D (triangular element: 3 nodes)
     - 2.5D (multiple 2D elements in inter-related layers)
     - 3D (block elements: 9 nodes)
  3. Mold and Plug geometries
  4. Parts dimensions (shrinkage and deformation)
4. Inputs required (1 of 7)

1. Mold and plug geometries

- Temperature of mold and plug
- Temperature *uniform* OR *variable (choice)*
- Heat transfer coefficient for ALU or other material
- ...

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2. **Material data: (from database)**

- For **specific type of plastic**

- From a **commercial formulation OR material characterization** (as rheology model, specific heat, density, conductivity, absorption, crystallinity, molecular orientation, permeability, ...)

- **Uniform OR multi-layer** *(option)*

- ...
3. Sheet dimensioning and frame

- Dimensions of sheet for molding station
- Sheet thickness
- Holding frame
- Mesh size to define (FEA) (# of nodes)
  - 37,913 nodes and 74,744 elements
- Others:
  - Air temperature, Coefficient of transfer, ...
4. Sheet reheating

- Dimensions of oven *(length, width)*
- # of heating zones *(up and down)*
- Heaters distance *(up and down)* from sheet
- Temperature of each zone
- Emissivity of heaters, ...
- Air properties in the oven
- ...
5. Mold and Plug displacements (Pre-forming)

- Initial Position
- Final Position
- Displacement under a specific time (i.e. velocity)
- ...

[Diagram of mold and plug displacements]
5. Vacuum and-or Pressure application (forming)

- Defined time of application
- Delay if any
- Pressure
- Air temperature, heat transfer, ...
- ...

...
## Processing Conditions (as per cycle time)

<table>
<thead>
<tr>
<th>Cumulative time (sec)</th>
<th>Time of steps</th>
<th>Processing Operation and # steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3</td>
<td>1.58/3.15/4.72/6.30</td>
<td>1. Sheet Reheating (in 4 steps)</td>
</tr>
<tr>
<td>6.4</td>
<td></td>
<td>2. Sheet Transfer Air properties</td>
</tr>
<tr>
<td>6.5</td>
<td>6.42/6.44/6.46/6.48/6.50</td>
<td>3. Mold Displacement (in 5 steps) Plug Displacement</td>
</tr>
<tr>
<td>7.1</td>
<td>6.62/6.74/6.86/6.98/7.10</td>
<td>4. Pressure-vacuum Application (in 5 steps)</td>
</tr>
<tr>
<td>8.8</td>
<td></td>
<td>5. Cooling in mold</td>
</tr>
<tr>
<td>11.8</td>
<td></td>
<td>6. Cooling outside the mold</td>
</tr>
</tbody>
</table>

- **Pre-stretching** (0.1 sec)  
- **Stretching** (0.6 sec)  
- **3 strokes**
Run the simulation …

As per requirement, the software runs the simulation (calculation time)

• Resolving ALL equations until a converged solution is obtained for ALL nodes

• Calculation time function of:
  • Number of nodes (37,791 nodes)
  • Number of steps and sub-steps (55 steps and sub-steps)
  • Number of iterations to converge (50 max.)
  • ...

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Simulation (graphic representation)
Pre-Stretching (plug & mold movements)

75 mm in 30 sub-steps

Conduction

slip

Convection
Pre-Stretching (plug movement)

75 mm in 30 sub-steps
Pre-Stretching (plug & mold movements)

75 mm in 30 sub-steps

Pre-Stretching

Conduction

Convection

slip
Time before stretching by application of vacuum
Stretching (vacuum)
5. Results (WTD) obtained from simulations

- Regular plug geometry. (P0 or REF)
5. Results (WTD) obtained from simulations

1st serie of plug geometries (REF, P1, P2, P3, P4, P5)

(a) (b) (c)

(d) (e) (f)
Plug P5 during pre-stretching
Results (WTD) obtained from simulation

- 2nd serie of plug geometries (P6, P7, P8)
A results recapitulation

![Graph showing results comparison between REF, P1, P2, P3, P4, P5, P6, P7, P8 with thickness indicated in millimeters.]

- REF: [Graph showing thickness distribution]
- P1: [Graph showing thickness distribution]
- P2: [Graph showing thickness distribution]
- P3: [Graph showing thickness distribution]
- P4: [Graph showing thickness distribution]
- P5: [Graph showing thickness distribution]
- P6: [Graph showing thickness distribution, with a label showing 0.023""]
- P7: [Graph showing thickness distribution]
- P8: [Graph showing thickness distribution, with a label showing 0.008"]
Stretch Ratio on P6, P7 and P8
From simulation’s results, a “real” production run ...

Minimum QC specs

- Bottom : 0.355 mm (14 mil)
- Sides : 0.255 mm (10 mil)
- Corners : 0.225 mm (9 mil)
5. Simulated results and production results
Outcomes

In plug design (and for similar part geometry)

1. Minimize surface plug-sheet contact
2. Remember that slip conditions are function of
   - Plug material and Coefficient of Friction
   - Plug temperature
   - Plug radius as well
   - ... Surface roughness may play a role
3. Get contact only in specific area that may required better control on wall thickness
4. Control plug velocity to adapt to the material behavior
6. Benefits of using software to simulate process

- Reduction of debugging time (new products-parts)
  - big part of the job in already done

- Reduction in raw material costs
  - Significant savings

- Better use of Process Technician and Engineer time:
  - But use their significant inputs and know-how

- Potential savings on tooling reworks
  - CAD modifications and several simulations are easy to run
Benefits of using software to simulate process

- Gain in machine-time (efficiency)
  - 10 new molds/yr X 15 hrs = 150 hrs. X 35 $/hr = 45 000 $ / year
    (add. Potential Profit)

- Possible lower sheet gage
  - Even 1 mil reduction can be 5 -8% cost reduction in raw material costs
    5 - 20 000 $ / yr

- Better understanding of thermal material behavior in the process
- Reduced time to production
- Better understanding of the optimization-technology process
Costs related

- Annual software license fee
- Engineer(s) trained to use and understand its potential
- Good CAD supporting team
- Good production team opened to new aided technology

OR

- Use of professional engineering firm to do the simulation(s)
Thanks you!

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