Issues and Opportunities in the Development of High Strength Glass Containers

Emilio D. Spinosa
Senior Glass Scientist
PacRim 2009 Special Session
June 4, 2009
Outline

• Why Work On Glass Containers?
• Technical Challenges To Enhancing Glass Container Strength.
• Measuring Glass Container Strength.
• Industry Attempts To Enhance Glass Container Strength.
• Current Status and Needs For The Future.
Acknowledgements

• O-I
  – Robert Lachmiller, VP AGT
  – Douglas Trenkamp
  – Terence Howse
  – Ronald Myers
  – Carol Click
  – William Kilpatrick

• GPI
  – Kristen LeKander
Why Improve Glass Container Strength?
US Glass Container Industry

~ 50 Plants
33 States
US Glass Container Industry

~ 15,200 Employees
US Glass Container Industry

## 2008 Glass Container Shipments & Production

<table>
<thead>
<tr>
<th>Shipments</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>242,205</td>
<td>237,648</td>
</tr>
<tr>
<td>242,444</td>
<td>244,689</td>
</tr>
</tbody>
</table>

Source: U.S. Dept. of Commerce, Bureau of the Census
Data reported in thousands gross. One thousand gross = 144,000

~ 35 Billion Containers Annually
Consumer Preference for Glass Containers

But.....
Consumer Aversion for Glass Containers
Higher Strength ➔ Less Weight

~ 2.5* MJ/container

-10% Weight

~ 2.2 MJ/container

*US DoE and Bureau of Census Data

SO\textsubscript{X} + CO\textsubscript{2} + NO\textsubscript{X}
Benefits of Improving Glass Container Strength

• Help an Industry That Is an Important Part of US Economy

• Help Satisfy Consumer Preference
  – Reduce Hurdle to Increased Use of Glass Containers

• Improve Green Footprint
  – Energy Saved
  – Reduced Fossil Fuel Usage
    – Smaller Carbon Footprint
  – Reduced Emissions
What Are the Technical Challenges Hindering Increase of Practical Glass Container Strength?
Surface Strength Of Glass Containers (psi)

Surface Strength Of Glass Containers (psi)

- High Strength Alloys
  - ~ -25% Weight
  - Theoretical: \( \approx 3 \text{KK} \)
  - Pristine Fiber (As Drawn)

- Used: 2.5 - 4.5K (Visible Damage)
- Shipped: 6.5 - 7.5K
- Formed: 10 - 12K
- NonReturnable
- Returnable

Glass Container Strength

• Working Definition Affected By:
  – Shape and Use
  – Forming Method
  – In-plant Processing
  – Customer Handling
  – Consumer

• Each Additional Step Potentially Adds Strength-Limiting Flaws
Influence of Manufacturing Process
Strength-Related Container Design

- Design For Worst Case
  \[
  \frac{\text{Diameter} \times \text{Pressure}}{(2 \times \text{Expected Surface Stress})} = \text{Minimum Glass Wall Thickness}
  \]

- Protect Vulnerable Regions
  - Thicker
    - Shoulder Contact
    - Heel Contact
  - Bearing Surface Knurling

- Extra Features Add Weight
How Is Glass Container Strength Measured?
Line Simulator
Internal Pressure

Carbonated Beverages:
• Produce Internal Pressure
• Develop Tensile Stress on Exterior Surface
Internal Pressure Failure (IPF)

- Shoulder Contact
- Heel Contact
- Side Wall
- Bearing Surface
Internal Pressure Failure Test

Fill with Water.

Increase Water Pressure Until Failure Occurs.
Internal Pressure Failure Test (Improved)

Wrap Bottle With Tape To Preserve Failure Origin.
Internal Pressure Failure Test (Improved)

Locate Failure Origin.

Carefully Collect Failure Origin.

Crucial Steps for Obtaining Accurate Failure Stress Data.
IFP Stress Measurement

Typical Failure Site

Measure Mirror Diameter.
IPF Stress Measurement

- Mirror, Mist, Hackle

- $s_f \sqrt{R_i} = A_i$
Sources of Impact Failure

- Flexure Stress
- Hinge Stress
- Contact Stress

High Strength Glass Containers: Issues and Opportunities
Calculated Impact Load

76 cm/sec Impact

Graph showing the relationship between Inside Surface Stress (GPa) and Sidewall Thickness (mm). The graph includes a design limit and a safe design point.
Impact Testing (Important Design Parameter)

Each Gear Tooth Calibrated To Impact Velocity.

Fixed Mass.
Good Indication of Impact Strength:
- Imprecise
- Not Robust

Increase Velocity Until Impact Failure Occurs.
Glass Container Strength Data

• Caveat Regarding IPF In Literature
  – Often Failure Pressure Data Not Failure Stress Data
  – Usually No Account Taken Of Wall Thickness
  – Older Data Less Reliable Because Wall-thickness Control Poorer

• Beware Of Poor Statistics
  – Mean Only
  – No Standard Deviation
  – No Weibull
What Do Glass Container Manufacturers Seek from Increased Working Strength?
Current Practice (40 Years)

- Strength Preservation
  - [US 3,323,889 (1967); CA 853,121 (1970)]
    - SnO$_2$ Coating (Discontinuous)
      - Just After Bottle Formed (Hot-End Coating)
      - CVD
    - Polyethylene Emulsion (Water) Sprayed Onto Bottle Just After Annealing
      - Cold-End Coating
    - Add Lubricity to Minimize Additional Flaw Generation
    - No Flaw Healing
Pursuit of Strength-Enhancing Technology for Glass Containers

- Heal or Blunt Strength-Reducing Flaws
- Eliminate Low-Strength Tail of Distribution
  - Increase Mean Failure Stress
- Decrease Influence Inside Surface Flaws
- No Decrease to Process Speed
  - 600 bottles/minute
Glass Container Strength

Weibull Cumulative

<table>
<thead>
<tr>
<th>Failure Stress, MPa</th>
<th>Probability of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

RETURNABLE
40 TRIPS
AS PRODUCED
NON-RETURNABLE

Failure Stress, MPa

Probability of Failure
Flaw-Healing Coating

Weibull Cumulative

Probability of Failure

Failure Stress, MPa

Organic

AS FORMED

COATED

High Strength Glass Containers: Issues and Opportunities
After Coating:
- Majority of Distribution More Narrow
- Multimodal
  - Some Very Weak
  - Some Very Strong
- Large Overlap of Low-Strength Tail
- No Change to Mean
- Weak Evidence of Healing
- Typical Result
  - Stronger Are Stronger
  - Weak Unchanged
Protective Coating

Weibull Cumulative

Failure Stress, MPa

Probability of Failure

AS FORMED

COATED

Failure Stress, MPa

0.00

0.05

0.10

0.15

0.20

0.25

0.30

0.35

0.40

0.45

0.50

0.55

0.60

0.65

0.70

0.75

0.80

0.85

0.90

0.95

1.00

0

25

50

75

100

Organic

High Strength Glass Containers: Issues and Opportunities
After Coating:
- Distribution Broader
- No Longer Multimodal

- Low-Strength Tail
  - Minimal Overlap
    - Perhaps None
- Higher Mean

Potentially Useful For Reducing Returnable Bottle Weight
Strength Enhancing Technologies

Develop Surface Compression 30-40 MPa

• Thermal Tempering
  – Blow Cold Air Onto Surface To Quench It
    o Resist contraction of hotter, interior glass

• Chemical Tempering
  – Exchange Larger Ion for Smaller (ca $T_g$)
    o Resist contraction of bulk glass

• Surface Layer of Lower Thermal Expansion
  – $2^{nd}$ Glass
    o Duraglas XL® (O-I Patents)
Thermal Tempering

- Sound Physics
  - Can Treat Exterior and Interior Surfaces
- O-I (ca. 1960)
  - Wall Thickness Variation Very Critical
  - Process Control Inadequate
  - Spontaneous Failure Occurred
- Another Company Recently Filed Several Patents
  - Data Is Sparse
  - Progress Should Be Followed
Chemical Tempering (Ion Exchange)

Brockway Glass & Domglas
[US 3,218,220] [US 4,134,746]

- Spray Solution K-salt Onto Bottle
  - After Forming
  - Before Lehr
- Heat Treat
  - 850 = °F = 900
  - 1 = Hours = 2
- Successfully increase strength
- Long, Complicated Process
  - Deterred Implementation

![Graph showing IPF (psi) for Control, KF+Zn(OAc)2, and KPO4 in Formed and Line Simulation stages.](image-url)
Chemical Tempering (Ion Exchange)

CocaCola [US 24,221,615A1]
Duraglas XL®: 2nd Glass Layer

~ 0.1 mm

~ 13.1 MPa Compression
Duraglas XL® Delivery System
Duraglas XL®

Coated: \( \text{SnO}_2 \) (Hot End)
Polyethylene Emulsion (Cold End)
High Strength Glass Containers: Issues and Opportunities
Duraglas XL® Lightweighting

- Standard
- Improved (-13%)
- Optimized (-26%)

Bar chart showing:
- Internal Pressure
- Shoulder Impact
- Heel Impact

IPF (psi) and Impact (ips) values for each category.
Duraglas XL® Lightweighting

Same Shape: -13%

External Surface Dominance
(IPF)

Internal Surface Dominance
(Impact)

Shape Optimized: -26%
What is the Industry’s Current Status?
Glass Container Manufactures:

• Have History Of Trying To Improve Strength Performance
  – Organic Coatings
    o Flaw-healing
    o Strength-maintenance
  – Surface Compressive Layers
    o Thermal Tempering
    o Chemical Tempering
    o 2nd Glass Layer

• Efforts Frustrated By Complicated Manufacturing Process
  – Successful Technically
  – Unsuccessful Commercially
    o Complicated Processing Difficult to Implement
What Does the Industry Need to Make Progress?
New Strength-Enhancing Technology Should:

Technically:

- Heal or Blunt Flaws
- Eliminate Low-Strength Tail (Must)
  - Increase Mean Failure Stress (Bonus)
- Match Returnable Performance At Nonreturnable Thickness
- Decrease Influence Inside Surface Flaws
- Compatible with Container Glass Chemical Composition
New Strength-Enhancing Technology Should:

Industrially:

- Accommodate Wide Range Forming Machine Speed
  - Up to 600 Bottles/Minute
- Integrable into Current Production Process
  - Insert at Earliest, Practical Location
    - Minimize Additional Damage
Benefits from Technically **and** Commercially Successful Strength Enhancing Technologies:

- **Reduction in Glass Container Weight**
  - Reduce Energy Required to Melt Glass for Container Production
    - Reduce Natural Gas and Oil Consumption
    - Reduce Green House Gases
    - Reduce Other Emissions

- **Increase Use of A Preferred Product By Consumers**

- **Help Sustain An Important US (And World-wide) Industry**
Thank you for your attention and the opportunity to discuss glass container strength.

Questions?

Comments.