Flat Glass Production Using the Float Process

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Contributions by Chuck Edge
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Presentation Outline

Float Process History

Process Tour
  Glass Delivery System
  The Float Bath
  The Bath Exit

The Equilibrium Thickness Concept
Ribbon Forming
Optical Distortion
Heat Transfer
Bath Chemistry
Bath Modeling
Float Process History
## Float Glass Manufacture
(A Brief Patent History)

<table>
<thead>
<tr>
<th>Inventor</th>
<th>Year</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bessemer (Brit.)</td>
<td>1848</td>
<td>annealer, fire-polisher</td>
</tr>
<tr>
<td>Lombardi (Ital.)</td>
<td>1900</td>
<td>capacitors</td>
</tr>
<tr>
<td>Heal</td>
<td>1902</td>
<td>first &quot;float glass&quot; patent</td>
</tr>
<tr>
<td>Hitchcock</td>
<td>1905</td>
<td>direct stretch concept</td>
</tr>
<tr>
<td>Heal</td>
<td>1925</td>
<td>melt directly on tin</td>
</tr>
<tr>
<td>Hitchcock</td>
<td>1928</td>
<td>unhindered lateral flow</td>
</tr>
<tr>
<td>Pilkington</td>
<td>1965</td>
<td>first Pilkington patent (U. S.)</td>
</tr>
<tr>
<td>Edge et. al.</td>
<td>1974</td>
<td>PPG process</td>
</tr>
</tbody>
</table>
An Early “Float” Concept

plate glass
skim kiln

“tin or lead”
The Direct Stretch Process
The Assisted Direct Stretch (ADS) Process
(to produce glass <equilibrium thickness)
The Reverse Assisted Direct Stretch (RADS) Process
(to produce glass > equilibrium thickness)
The PPG Process
Primary Glass Processes
U. S. Market Share

Percentage of Market Share (sq. ft. basis)


float    plate    sheet
Process Tour
Functions of a Float Bath

• Need to produce glass as flat as possible
  – Bottom surface becomes flat since liquid tin (very dense) provides flat surface
  – Top surface becomes flat by glass flow due to gravity

• Need to produce glass to needed thickness and width
  – ADS machines are used

• Need to cool glass from 1100 C to 600 C
  – Coolers are used at appropriate locations

• Tin must not get oxidized
  – Bath atmosphere kept reducing 95% N$_2$ + 5% H$_2$
Glass Delivery to the Tin Bath
Glass Delivery

CENTERLINE FRONT TWEEL

GLASS FLOW
Glass Delivery System
Glass Delivery System
The Float Bath
Glass flows onto the tin at a thickness of approximately 5 cm and spreads to achieve an equilibrium thickness of .6909 cm.

The lehr force is attenuating the glass to a final thickness less than equilibrium. The internal stress in the glass attempts to narrow the ribbon back to equilibrium thickness. The outward force imposed by the ADS machines minimizes the collapse to produce a ribbon of desired thickness and width.
Float Bath Cross Section

Cross Section of Bath

- N₂ + H₂ GAS FEED
- Refractory Roof
- Heating Elements (Candles)
- Top Roll Machine
- Refractory Bottom
- Steel Roof Casing
- Plenum
- Glass
- Tin
- Steel Casing

PPG Proprietary
The Bath Exit
Ribbon Removal from Float Bath
Equilibrium Thickness
Equilibrium Thickness

When molten glass is poured onto tin, it will spread until the interfacial tensions and gravitational forces are balanced, resulting in a circular glass-tin interfacial shape with an equilibrium thickness of 6.9mm.

When forming a continuous ribbon, the glass will always attempt to achieve equilibrium thickness.

If the glass thickness is less than 6.9mm, the ribbon will collapse to become thicker.

If the glass thickness is greater than 6.9mm, the ribbon will spread to become thinner.
Equilibrium Thickness - A Free Body Diagram

Equilibrium Thickness = 6.9mm

\[ h_{eq}^2 = \left( S_{tg} + S_{ag} - S_{ta} \right) \frac{2\rho_t}{g\rho_g \left( \rho_t - \rho_g \right)} \]
# Some Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density</strong></td>
<td></td>
</tr>
<tr>
<td>glass</td>
<td>2400 kg/m³</td>
</tr>
<tr>
<td>tin</td>
<td>6500 kg/m³</td>
</tr>
<tr>
<td><strong>Surface Tension</strong></td>
<td></td>
</tr>
<tr>
<td>glass/air</td>
<td>.318 N/m</td>
</tr>
<tr>
<td>glass/tin</td>
<td>.528 N/m</td>
</tr>
<tr>
<td>tin/air</td>
<td>.497 N/m</td>
</tr>
<tr>
<td><strong>Viscosity</strong></td>
<td></td>
</tr>
<tr>
<td>glass</td>
<td>10² to 10⁹ Pa-s</td>
</tr>
<tr>
<td>tin</td>
<td>.001 Pa-s</td>
</tr>
<tr>
<td><strong>Thermal Conductivity</strong></td>
<td></td>
</tr>
<tr>
<td>glass</td>
<td>1 W/m-K</td>
</tr>
<tr>
<td>tin</td>
<td>46 W/m-K</td>
</tr>
<tr>
<td>fused silica</td>
<td>1 W/m-K</td>
</tr>
<tr>
<td>Walsh 71 refractory</td>
<td>2 W/m-K</td>
</tr>
</tbody>
</table>
Ribbon Stress vs Thickness

Equilibrium Thickness
\( h_e = 6.9 \text{mm} \)

\[\sigma = \frac{-349}{h} + (742 \times h)\]

\( \sigma \) = Stress (Dynes/cm²)

\( h \) = Thickness (cm)
Ribbon Forming
Glass flows onto the tin at a thickness of approximately 5 cm and spreads to achieve an equilibrium thickness of 0.6858 cm.

The lehr force is attenuating the glass to a final thickness less than equilibrium. The internal stress in the glass attempts to narrow the ribbon back to equilibrium thickness. The outward force imposed by the ADS machines minimizes the collapse to produce a ribbon of desired thickness and width.
## Forces: An Example Using a Typical Float Bath Setup

<table>
<thead>
<tr>
<th>Force</th>
<th>First Machine (dynes)</th>
<th>Last Machine (dynes)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertia</td>
<td>0.04</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td>Hydrostatic</td>
<td>590</td>
<td>317</td>
<td></td>
</tr>
<tr>
<td>Surface Tension</td>
<td>-590</td>
<td>-750</td>
<td></td>
</tr>
<tr>
<td>Net</td>
<td>0</td>
<td>-433</td>
<td></td>
</tr>
<tr>
<td>Tin Friction (bottom surface)</td>
<td>5.5</td>
<td>113</td>
<td></td>
</tr>
<tr>
<td>Longitudinal Lehr Force</td>
<td>161</td>
<td>5279</td>
<td></td>
</tr>
<tr>
<td>(ribbon attenuation)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Tin Temperature and Ribbon Thickness

Tin Temps @ 100 mm from Ribbon edge

Cookie Cutter Data
ADS Machines

• Work in conjunction with attenuating lehr force to form ribbon thickness and width

• Impart angular force to top surface of ribbon for controlling ribbon width and speed

• Affect ribbon thickness contour

• Used for less than equilibrium thickness: ADS “Assisted Direct Stretch”

• Used for greater than equilibrium thickness: RADS “Reverse Assisted Direct Stretch”
Bath Thickness Calculation $T_i$

$V_i = V_f$

$T_i \times A_i = T_f \times A_f$

$T_i = T_f \times \frac{A_f}{A_i}$

$T_i = .086 \text{ in.} \times (4 \ 1/4 \text{ in.} \times 25 \ 7/16 \text{ in.}) / 36 \text{ in}^2.$

$T_i = .258 \text{ in.}$

$V_i = \text{initial volume} \quad V_f = \text{final volume}$

$T_i = \text{initial thickness} \quad T_f = \text{final thickness}$

$A_i = \text{initial area} \quad A_f = \text{final area}$
Prediction of cookie cutter data is a very sensitive test of the model, great for model validation.
Sand Trace Velocity Profile

180 Metric TPD  2.5mm
322 cm   103.5 mm/sec

Flow
Optical Distortion
Float Glass: A Typical “Semi-Schlieren” Photo

The pattern is characterized by:

uniformity
directionality
Optical Distortion in Float Glass

uncorrelated thickness variations

corrugations

highly anti-correlated variations ("varicose", "sausages")
Refraction, Snell’s Law

Snell’s Law: \( n_1 \sin \phi_1 = n_2 \sin \phi_2 \)
Properties of Lenses

R, S are radii of curvature
n is index of refraction

The lensmaker's equation:

\[
1/f = (n - 1)(1/R + 1/S)
\]

f = focal length

P = optical power (diopters)

\[
P = 1/f
\]
Float Glass Quality: Qualitative Features

- Reduced distortion levels over time
- Improved internal quality
- Optical quality degrades with reduced thickness
- Optical quality degrades with increased throughput
- Product standards are generally independent of thickness
Float Glass Manufacture

Sources of Optical Distortion

- internal quality
- poor refractories
- bath hardware/machines
- exit end

“housekeeping”, or passive variables

- ribbon cooling
- viscous stresses
- tin flows

“process”, or active variables
Float Glass: Transmitted Distortion

• There are two basic sources of transmitted distortion, glass inhomogeneities and surface irregularities.
• The glass inhomogeneities originate in the furnace.
• The surface irregularities originate in the hot end of the float bath, and are caused by cooling the ribbon.
• Both have a complex bath processing component.
Model Validation:
Transmitted Distortion

- ribbon speed
- visual zebra angle
- internal quality
- cooling/heating configuration
Model Validation: Reflected Distortion

optical power

ribbon speed
Sag (distortion)

\[ \text{Sag (distortion)} = K \left( \frac{\rho g}{\mu} \right) \left( \frac{d^5}{vh^2} \right) \]

\[ = K \left( \frac{\rho g}{\mu} \right) \left( \frac{Wd^5}{Qh} \right) \]

Thus, exit end distortion is inversely proportional to the ribbon viscosity and the ribbon thickness.
Heat Transfer
Heat Transfer – General Comments

• Heat transfer processes in the tin bath are quite complex
• All three modes of heat transfer (radiation, convection, and conduction) are taking place simultaneously.
• Glass is diathermaneous.
Heat Removal by Water Coolers

\[ Q = MC\Delta T \]

- **M** = amount of water (kg)
- **C** = specific heat of water: 1 cal = \( \frac{1000}{1000} \) cal/kg\(^{\circ}\)C
- \( \Delta T \) = temperature change of water (\(^{\circ}\)C)

**Example:** A cooler with a water flow of 378 l/min and a \( \Delta T \) of 9\(^{\circ}\)C

\[ Q = (378 \text{ l/min}) \times (1 \text{ kg/l}) \times (60 \text{ min/hr}) \times (1000 \text{ cal/kg}^{\circ}\text{C}) \times (9^{\circ}\text{C}) \]

\[ Q = 204,120,000 \text{ cal/hr} = 854,650 \text{ kJ/hr} \quad 1\text{ kW} = 3600 \text{ kJ/hr} \]

\[ Q = 238 \text{ kW} \]

**Shortcut**

\[ Q (\text{kW}) = \text{l/min} \times \Delta T \times 0.07 \]

\[ Q = 378 \text{ l/min} \times 9 \times 0.07 \]

\[ Q = 238 \text{ (kW)} \]
Bath Chemistry
Metal Substrate Requirements

- Denser than glass
- Minimal chemical reactivity with glass
- Glass doesn’t “wet” it
- Boiling point well above 2000 °F
- Melting point below 1100 °F
- Low vapor pressure
- Manageable metal chemistry
- Affordable
## Properties of Various Metals

<table>
<thead>
<tr>
<th>METAL</th>
<th>MELTING POINT °F</th>
<th>BOILING POINT °F</th>
<th>VAPOR PRESSURE @2000°F mmH</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIN</td>
<td>450</td>
<td>4120</td>
<td>.002</td>
<td></td>
</tr>
<tr>
<td>GALLIUM</td>
<td>86</td>
<td>3600</td>
<td>.023</td>
<td>WETS GLASS</td>
</tr>
<tr>
<td>INDIUM</td>
<td>313</td>
<td>3630</td>
<td>.11</td>
<td></td>
</tr>
<tr>
<td>ALUMINUM</td>
<td>1220</td>
<td>3733</td>
<td>.45</td>
<td>WETS GLASS, FORMS NITRIDE</td>
</tr>
<tr>
<td>BISMUTH</td>
<td>520</td>
<td>2588</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>LEAD</td>
<td>621</td>
<td>3270</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>BARIUM</td>
<td>1340</td>
<td>2980</td>
<td>15</td>
<td>FORMS NITRIDE</td>
</tr>
<tr>
<td>ANTIMONY</td>
<td>1168</td>
<td>2625</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>CALCIIUM</td>
<td>1553</td>
<td>2710</td>
<td>32</td>
<td>FORMS NITRIDE</td>
</tr>
<tr>
<td>THALLIUM</td>
<td>576</td>
<td>2637</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>STRONTIUM</td>
<td>1420</td>
<td>2523</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>CERIUM</td>
<td>1480</td>
<td>2550</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>GERMANIUM</td>
<td>1720</td>
<td>4900</td>
<td>.00003</td>
<td></td>
</tr>
<tr>
<td>SILVER</td>
<td>1762</td>
<td>3540</td>
<td>.027</td>
<td>COULD USE OXIDIZING ATM.</td>
</tr>
<tr>
<td>GOLD</td>
<td>1945</td>
<td>4710</td>
<td>.00001</td>
<td></td>
</tr>
<tr>
<td>COPPER</td>
<td>1980</td>
<td>4237</td>
<td>.0003</td>
<td></td>
</tr>
</tbody>
</table>
Properties of Tin

- Melting Point = 232 °C
- Boiling Point = 2271 °C
- Vapor Pressure = 0.002 mm Hg @ 1100 °C
- Density = 6.5 g/cc
- Low viscosity at bath temperatures (0.01 p)
- Low reactivity/solubility with H₂ and N₂
- High reactivity with O₂
- Does not wet the glass
Oxygen Cycle

Bath Atmosphere N2 + H2

2 SnO(\text{g}) = Sn + SnO2

\Delta H

SnO2 + 2 H2 = Sn + 2 H2O

\Delta H

Air leaks

1900^\circ F

1100^\circ F

SnO2

SnO

O2

Tin
Solubility of Oxygen in Tin

Data taken from Belford and Alcock.
SnO$_2$ Reduction by H$_2$

SnO$_2$ + 2 H$_2$ $\Leftrightarrow$ Sn + 2H$_2$O
Sulfur Cycle

SnS\textsubscript{(g)}(g) + H\textsubscript{2} = Sn + H\textsubscript{2}S

Bath Atmosphere N\textsubscript{2} + H\textsubscript{2}

heat

\Delta H

vents

Sulfur

1900^\circ F

1100^\circ F

Tin
Solubility of Sulfur in Tin

Actual Measured Sulfur in Tin, ~ 2 to 10 ppm

<table>
<thead>
<tr>
<th>Temperature °F</th>
<th>Vapor Pressure SnS (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1101</td>
<td>0.01</td>
</tr>
<tr>
<td>1301</td>
<td>0.1</td>
</tr>
<tr>
<td>1400</td>
<td>1.0</td>
</tr>
<tr>
<td>1652</td>
<td>10.0</td>
</tr>
<tr>
<td>1850</td>
<td>100.0</td>
</tr>
</tbody>
</table>
A Bath Atmosphere Management System

- **H₂ usage:** 1% - 5% throughout the bath

- **N₂ usage:** 50,000 – 100,000 scfh (size dependent)

- **Bath pressure:** 0.20” H₂O or higher

- **Hot end venting:** vent 15-20% of the total atmosphere flow
Bath Modeling
Modeling Float Bath

- Three major computation fluid dynamics areas
  - Bath atmosphere flow
    - Effects bath defects like top tin
  - Glass flow
    - Need to make glass in needed thickness and width
  - Liquid tin flow
    - Influences glass temperature since tin is a liquid metal
Plan View of A Float Glass Tin Bath

~ 60 m

Glass

from

Tank

Sizing Machines

Typical Values

1100
Temperature (C)

600

$10^2$
Viscosity (Pa-s)

$10^9$

10
Glass Thickness (mm)

3

Massive glass viscosity variation $1:10^7$
Glass aspect ratios are large - Length:Width:Thickness = 10,000:1,000:1
Modeling Glass in Bath

- PPG has a detailed model
- Free surface model since glass thickness and width need to be calculated
- Inputs – Bath conditions (throughput, temperatures, machine speeds and angles, exit speed)
- Output
  - Glass thickness and width
  - Glass speed (residence time)
  - Glass stresses
Model Predictions
Top View of glass in float bath

Streamlines

Glass speed

Glass thickness
Tin Flow Modeling

- Liquid metal flow – high thermal conductivity
- Turbulent
- Moving glass drags thin boundary layer of tin
- Return flow along the sides
- Near bath entrance tin flow may laminarize
Typical Tin Flow Pattern at Exit End

Velocity Scale (inches per minute)

- 240
- 180
- 120
- 60
- 0

Tin flow 10 feet from exit end
Modeling Bath Atmosphere

- Composition generally 95% $N_2 + 5% H_2$
- Turbulent gas flow
- Buoyancy effects due to bath temperatures
- Lot of variation from bath to bath since baths conditions vary
References


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January 25, 2015