Lecture 9:
Manufacturing of paperboard and corrugated board

Runnability and quality parameters

After Lecture 9 you should be able to

- describe the major process steps in manufacturing of paperboard and corrugated board
- discuss the most important quality parameters of packaging paper and board, and the methods used to determine them
Literature

- Fundamentals of packaging technology – Chapters 5 and 15
- Paperboard Reference Manual, pp 31-44
- Cartons, Crates and Corrugated Board – Handbook of Paper and Wood Packaging Technology - Chapter 7

Runnability – A material property?

Quality parameters?

Testing of paperboard and corrugated board is required.
The purpose of testing is:

• to control production processes
• to ensure uniformity of the product
• to predict performance of the product
• materials design

Paperboard and corrugated board testing is only an approximation or projection of expected performance!
The paperboard manufacturing process

Process steps in the paperboard machine

- Stock preparation
  - Beating of fibres
  - Diluted suspension
  - Functional chemicals added
- Multi-ply forming
- Press section
- Drying section
Post-drying operations in a paperboard machine - I

- **Machine glazing**
  - Drying of the wet surfaces in contact with polished steel cylinders to produce a smooth surface with minimum loss of thickness and stiffness

- **Surface sizing**
  - Starch solution (sometimes pigmented) applied on one or both sides to improve strength, smoothness and printability

- **Calendering**
  - Paperboard nipped between steel rollers to achieve uniform thickness and surface smoothness, typically reduces bending stiffness.

Post-drying operations in a paperboard machine - II

- **Surface coating**
  - White pigmented coating (mixture of clay and latex) applied in liquid form
  - Improves
    - Surface smoothness
    - Whiteness
    - Results in uniform ink and varnish absorption

- **Surface finishing**
  - Gloss calendering
  - Brush burnishing
Other important processes in paperboard manufacturing

- Reel up
- On-line measurements and control
- Re-winding and slitting
- Sheeting

Paperboard quality parameters are related to

- Appearance and surface properties
  - Typically related to printability, varnishability and print quality
  - Slipperiness of the board
  - Moisture resistance
  - Gluability
- Physical performance properties
  - Stiffness and strength properties that are typically related to converting, stacking and end-use
**Appearance properties**
Printability

Paperboard with good and bad printability, respectively

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**Physical performance properties**
Stacking strength

Package failure
Surface and appearance properties

- Surface strength
- Surface tension
- Whiteness and brightness
- Opacity
- Surface roughness
- Gloss
- Friction
- Surface pH
- Ink absorption
- Rub resistance

Surface strength
Printability and varnishability

Delamination due to poor surface strength
**Surface strength**

IGT printability test – Measures force but not deformation

Simulation of offset printing.

Affected by
- type of fibre (long – short)
- treatment of fibres (beating)
- surface sizing
- type of coating pigment
- type and proportion of binder in the coating

**Surface tension**

Printability and varnishability

When the surface tension is too low for printing or gluing (typically a plastic surface), the surface can be treated by an electric corona discharge, which gives a slight oxidation of the surface.
Appearance properties

Appearance characteristics relate to the behaviour of light striking the paperboard surface.

**Appearance properties**

**Whiteness**

Paperboard with various white hues
Appearance properties

Brightness

Brightness is a measure of the reflectance of blue light at a single wavelength of 457 nm.

Whiteness and brightness

The stimulus from which the brain (or an instrument) interprets the colour.
Whiteness and brightness
Reflectance of light

Whiteness and brightness properties are highly dependent on:
- Coating composition
- Pigment type
- Coating grammage

Parameters affecting the impression of whiteness and brightness

- Adding FWA (Fluorescent Whitening Agent, absorbs some wavelength)
- Adding dyestuffs (coloured substances)
- Bleaching

Whiteness and brightness are usually very important in design of packages for luxury products.
Appearance properties
Surface roughness - Bendtsen

Tests operate on the principle of forcing air out along the surface of the board.

The requirement on surface smoothness depends on print method used and on the required print result.

Appearance properties
Gloss

Gloss is the measure of light directly reflected from a surface
**Surface properties**

**Friction**

Measurement of paper-to-paper friction

The frictional properties of paper are determined by the surface roughness and, more importantly, by the chemistry of the paper surface.

Johansson, Fellers, Gundersson & Haugen, 1998

Garoff, 2002

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**Surface properties**

**Gluability**

Gluability is determined by the amount of fibre that is pulled from the paperboard when the glue line is separated.
Appearance properties

Absorption and drying

- Surface pH
  - important for the ink-drying process and for inks containing metal pigments (a pH of 6-8 is normally required)

- Ink absorption
  - measured from brightness of surface from which the ink has been wiped off after a specified time

- Rub resistance

Absorption and evaporation

Absorption and setting

Physical performance properties

- Strength and toughness
  - Tensile strength
  - Tearing resistance
  - Delamination strength
  - Bending stiffness
  - Bending resistance
  - Compression
  - Fracture toughness
  - Box compression strength (BCT)

- Flatness and dimensional stability

- Creasability and fold ability
  - Runnability

- Thickness
- Density
- Grammage
- Moisture content
- Gluability and seal-ability
- Clean edges and surfaces
- Taint and odour
Runnability
"Definition"
Possibility to run a material through a process with acceptable speed and with acceptable quality of the produced material.

- **Production (corrugated board):**
  - speed not reduced, limited warp and acceptable glue bonds

- **Converting:**
  - speed not reduced, good printing and no cracking in the material

- **Filling:**
  - speed not reduced, undamaged and properly sealed packages

Different professional organisations such as TAPPI, SCAN, ISO etc. have established standards and procedures to be followed when conducting paper and paperboard testing.
Physical characteristics relate to the fibre structure of the paperboard sheet

- Paperboard is highly **HYGROSCOPIC** – it absorbs moisture in humid conditions and releases moisture in dry conditions
- Paper exhibits **HYSTERESIS EFFECTS** – moisture content returns to a different level than the starting level during a moisture/drying cycle
- Therefore, standards require paperboard to be **PRE-CONDITIONED** prior to testing.

**Tensile strength**
Testing on a 15 mm wide paperboard strip

- Measures resistance of paperboard to pull apart or rupture and relates to internal fibre and fibre/fibre joint strength
- Increases with increase in basis weight
- Is measured in N/mm² or MPa
- MD tensile is in general greater than CD tensile
Tear strength

- “Measures internal tearing resistance”
- **THIS IS NOT REALLY A TEAR TEST, BUT A VERY UNSPECIFIED MIXED-MODE (DELAMINATION) TEST.**
- Tear strength increases with increased basis weight
- Tear strength is a function of fibre length
- CD tear strength is generally greater than MD
- Tear strength increases with increased moisture content in the paperboard

Performance properties

Delamination strength, ply bond strength

- **Peeling method**
- **Z-toughness method**

Testing requires the use of an adhesive or double-sided tape.
**Performance properties**
Delamination strength, ply bond

**Scott bond test**

![Diagram of Scott bond test](image)

Delamination energy

\[ W_{\text{critical}} = mg\Delta h \]

**Delamination energy**
Influence of basis weight (grammage)

![Graph showing influence of basis weight on delamination energy](image)

*Influence of adhesive used to mount the paper to the metal blocks*
Transferability?

![Diagram of paperboard and cylinder]

IGT = surface strength

Scott Bond, IGT (ggr 100)

Compression testing

- Compression testing indicates how the carton will resist crushing
  - Entire carton can be compressed
  - A corner of the carton can be compressed
  - A panel of the carton can be compressed
- Compression tests relate to the ability of the carton to withstand weight as in stacking during transit and warehousing or stacking on retail shelves
Performance properties
Strength and toughness

Compression strength

L & W, Markström, 1991

Physical performance properties
Bending stiffness

- Increases with increased thickness or grammage
- MD stiffness is generally greater than CD
- Virgin fibre paperboard will exhibit higher CD stiffness at a given basis weight that will recycled paperboard
- Bending stiffness is used to counter bulge
- Bending stiffness decreases with increased moisture content of the paperboard
Flatness and hygrostability
Curl because of …

• Moisture gradients

• Variation in fibre orientation, density

• Gradients in moisture expansion coefficient, elastic properties

Flatness and hygrostability
Curl - Influence of moisture

Paper curl depends on specimen size

Curl in offset printing
Curl because of through-thickness residual stresses

The mechanism behind build-up of residual stresses is moisture gradients during drying and re-wetting in combination with shrinkage due to changes in the moisture content.

Principle of detecting residual stress

\[
\alpha(z) = \frac{E(z_0 + z)\left(\frac{dN(z)}{dz} + v_K(z)\right)}{6(1 - \nu)\nu} + \frac{2E(z_0 + z)}{3(1 - \nu)\nu}K(z) (1 + v_K(z)) + \frac{E(z_0 + z)}{3(1 - \nu)\nu}K(z) (1 + v_K(z))
\]
Paperboard properties
Out-of-plane normal and shear

![Graphs showing normal and shear stress vs. displacement and shear displacement.]

Paperboard properties

Observations: Out-of-plane microscopic

Localized damage

![Images showing undeformed and deformed paperboard.]

Tensile loading


Tensile loading: Step 1
Tensile loading: Step 2

Tensile loading: Step 3
Tensile loading: Step 4

Tensile loading: Step 5
Tensile loading: Step 6

Tensile loading: Step 7
Tensile loading: Step 8


Shear loading

Shear loading: Step 1

Shear loading: Step 2
Shear loading: Step 3

Shear loading: Step 4
Shear loading: Step 5

Advanced "Established" methods

- Gluing
  - Glue penetration
  - Time consuming
- Alignment
  - Tilted gluing
  - Thickness
- Homogeneous stress field?
Testing the mechanical properties of paperboard in the thickness direction

Laminated Double Notch Shear test

- Ordinary tensile test
- No gluing
- Relatively fast
- Stress concentrations at notches
- Notches prepared on many test pieces in one step
Experimental Results
Different Grinding Depths

- Multi-ply Paperboard:
  - Outer areas stronger than inner ones
  - Minimum peak stress in middle of inner plies

![Graphs showing experimental results for multi-ply paperboard and kraftliner.]

Experimental Results
Different Grinding Depths

- Kraftliner:
  - No big variation in maximum stress at peak load for CD
  - The middle region is stronger in MD

![Graphs showing experimental results for kraftliner.]

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The corrugated board manufacturing process

3. Inside liner conditioning roll (preheating)  9. Glue
5. Glue  12. Slitting and scoring
7. Bridge  13. Cut off
8. Outside liner conditioning roll (preheating)  14. Piled delivery
Single-facer station

Double-backer station
Balanced or unbalanced constructions?

- **Balanced construction, for example 161/127C/161**
  - Outside liner 161 g/m²
  - Medium 127 g/m² formed to C-flute
  - Inside liner 161 g/m²
- **Unbalanced construction, for example 205/127C/161**
  - Outside liner 205 g/m²
  - Medium 127 g/m² formed to C-flute
  - Inside liner 161 g/m²

- Looking for small performance gain
- More problems with warpage
- Can be economically justifiable
- Better printing
  - Heavier liner placed on outside of box
- Better compression strength
  - Heavier liner placed on inside of box

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<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>Residence Time, ms</th>
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<tbody>
<tr>
<td>1</td>
<td>Preconditioning before the corrugator roll nip</td>
<td>—</td>
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<tr>
<td>2</td>
<td>Labyrinth entering the corrugator roll nip</td>
<td>6.0</td>
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<tr>
<td>3</td>
<td>Labyrinth leaving the corrugator roll nip</td>
<td>1.5</td>
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<td>4</td>
<td>Pressure compartment before the glue roll</td>
<td>94.5</td>
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<tr>
<td>5</td>
<td>Glue application</td>
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<td>6</td>
<td>Pressure compartment before the pressure roll</td>
<td>60.0</td>
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<td>7</td>
<td>Pressing the liner against the glued flute tips</td>
<td>1.15</td>
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<tr>
<td>8</td>
<td>Formation of the bond after the pressure roll</td>
<td>—</td>
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Corrugated board
Productivity - Runnability parameters

- Moisture
- Temperature
- Type of adhesive
- Web tension
- Production speed (web velocity)
- Paper qualities
  - Edge effects
  - Non-uniform mechanical properties
  - ...

Corrugated board
Production quality parameters

- Warp
- Gluing (bonds between liner and fluting)
- Surface (washboard, cockling)
- Sheet dimensions

<table>
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<th>Production data</th>
<th>1979</th>
<th>1989</th>
<th>1999</th>
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<tr>
<td>Basis weight (g/m²)</td>
<td>545/579</td>
<td>534/564</td>
<td>523/551</td>
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<tr>
<td>Deliveries (kton/year)</td>
<td>211/9087</td>
<td>282/12826</td>
<td>347/19352</td>
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<tr>
<td>Number of machines</td>
<td>21/7</td>
<td>18/704</td>
<td>12/876</td>
</tr>
<tr>
<td>Deliveries/machine (kton/year)</td>
<td>10/7</td>
<td>15.7/18.2</td>
<td>28.9/22.1</td>
</tr>
</tbody>
</table>
Corrugated board
Problem - Warp

- Properties and processes
  - Dimensional stability
  - Moisture difference between liners (affected by preheating)
  - Gluing
  - Drying
  - Web tension

Corrugating adhesives

- Typically a starch based adhesive
- Applied at about 10-14 g/m²
- Gelatinization temperature is typically 60-64 °C
- Starch does not tolerate high moisture and loses strength quickly
- In boxes where higher moisture resistance is needed starch can be modified or supported by various polymeric materials at a somewhat higher cost.
Testing of corrugated board at different structural levels

The corrugated box

Compression testing of the paperboard

Testing of corrugated board panels

Compression testing of corrugated board

FGT – Flat Crush Test measures the resistance of the flutes to a crushing force applied perpendicular to the surface of the board under prescribed conditions.

ECT – Edge Crush Test measures the edgewise compression strength, parallel to the flutes.
Compression testing of linerboard and fluting

RCT - Ring Crush Test for measuring the resistance of paper and paperboard to edgewise compression. A special jig is used during the test to hold the test piece in a ring form.

CTT - Corrugated Crush Test measures the edgewise compression strength of a laboratory-fluted strip of corrugated medium in the direction parallel to the fluted tips.

CMT - Concave Medium Test measures the crushing resistance of a laboratory-fluted strip of corrugated medium.

Euler buckling and compression strength

$\sigma_{cr} = \frac{4\pi^2E\nu}{\lambda^2} \quad [\text{N m/kg}]$

SLENDERNESS RATIO, $\lambda$

$\lambda = \sqrt{12\epsilon/t} \approx 3.46\epsilon/t$

Hinged ends

Fixed ends
Short Compression Testing

\[ \text{SCT} = \text{Short span Compression Test} \]

**COMPRESSION**

STFI Short-Span Compression Tester (SCT)
Compression strength RH

Transverse shear stiffness

\[ G = \frac{\tau}{\phi} \]
Box compression strength is a strong function of transverse shear stiffness

Torsion of corrugated board panels

\[
D_{QM} = \frac{M L}{\theta w}
\]

- \( D_{QM} \) = MD twisting stiffness, Nmm
- \( M \) = twisting moment, Nmm
- \( \theta \) = angle of twist, radians
- \( L \) = sample length between clamps, mm
- \( w \) = width of sample, mm
Damage during corrugation
What about influence on MD shear stiffness?

Flat Crush Test
CMT (Concora Medium Test)

Bending stiffness
4-point testing used for corrugated board to avoid influence of transverse shear

Burst strength
Biaxial strength

**BIAXIAL STRENGTH**

Experimental Method: Pressurized cylinder (internal pressure, $p$)

\[
\sigma_{\text{axial}} = \frac{pR}{2t} \quad \sigma_{\text{hoop}} = \frac{pR}{t}
\]

$t = \text{paper thickness}$
Biaxial failures

BIAXIAL STRENGTH
Paper Data and Prediction of Failure Criterion

Tsai-Wu failure criterion
Creep
Tension

Compression

Small strain levels relevant for boxes?
Bulge and strain
Mechano-sorptive creep on corrugated test pieces

Fig. 1. Typical creep response of specimens at 57% of maximum stress in cyclic (86–35%) and constant (90%) RH environments (semi-logarithmic plot).

After Lecture 9 you should be able to

- describe the major process steps in manufacturing of paperboard and corrugated board
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