Thermal Load And Heat Transfer Regarding EBPVD Of Plastic Web And Thin Metal Foils

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Thermal load and heat transfer regarding EBPVD of plastic web and thin metal foils

Outline

- Introduction
- Thermal effects in PVD deposition processes
- Coating of plastic webs
- Thin metal foil coating
- Experimental investigations
- Conclusions
# Applications of web coating

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Substrate thickness</th>
<th>Layer</th>
<th>Layer thickness</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET</td>
<td>0.6...10 µm</td>
<td>Al</td>
<td>50 nm</td>
<td>capacitors, packaging</td>
</tr>
<tr>
<td>PET</td>
<td>50 µm</td>
<td>TiO₂</td>
<td>45 nm</td>
<td>holographic foils</td>
</tr>
<tr>
<td>PET</td>
<td>25 ... 50 µm</td>
<td>Ag, ITO multilayer</td>
<td>250 nm total</td>
<td>solar control coating</td>
</tr>
<tr>
<td>TAC</td>
<td>80 µm</td>
<td>SiO₂, TiO₂ multilayer</td>
<td>250 nm total</td>
<td>AR coating</td>
</tr>
</tbody>
</table>
Fractions of substrate heat load in PVD processes

Total power density at the substrate $p_{\text{sum}}$

$$p_{\text{sum}} = p_C + p_R + p_P$$

with

- $p_C$: condensation heat load
- $p_R$: thermal radiation
- $p_P$: energy of particles
<table>
<thead>
<tr>
<th>Fraction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_C$</td>
<td>condensation heat load - layer, thickness</td>
</tr>
<tr>
<td>$p_R$</td>
<td>thermal radiation - evaporant, crucible</td>
</tr>
<tr>
<td>$p_P$</td>
<td>energy of particles – back scattered electrons</td>
</tr>
</tbody>
</table>

![Diagram of EB-Gun](image)
Energy balance for typical EB evaporation process from ceramic crucible

100% total EB energy impact toward the crucible

1. X-Radiation
2. Heat radiation to the strip
3. Heat radiation into the chamber
4. Heat conduction through the crucible wall
8. Reflected electrons into chamber
5. Reflected electrons to the strip
4. Scattered electrons to the strip
14. Scattered electrons to chamber wall
21. Scattered evaporation to the chamber
31. Evaporation

Amount of energy impact / %

Schiller, ... Electron Beam Technology Verlag Technik Berlin, 1982
Arrangement of EB metal strip coating
EB metal strip coating arrangement with cooling drum
EB metal strip coater EBA 370 A1
Batch type web coater for EB deposition

1 Unwinder
2, 9, 11 Guide roller
3, 10 Spreader roller
5 Coating drum
4, 6, 8 Tension measurement roller
6, 8 Measurement roller
7 Tension isolation roller
12 Rewinder
13 Crucible
14 Magnetic trap
M Optical Measurement

EB Gun
Magnetic trap for EB evaporation processes
EB evaporation process with magnetic trap
Web temperature and heat transfer coefficient

Calculation of web temperature:

\[ \Delta T = \frac{P_{\text{sum}}}{k} \left( 1 - e^{-\frac{k \cdot l}{v d \cdot \rho \cdot c}} \right) \]

with:
- \( \Delta T \): Temperature difference
- \( P_{\text{sum}} \): Total power density at the substrate
- \( k \): Heat transfer coefficient (web to cooling drum)
- \( \rho \): Density of the web material
- \( d \): Thickness of the web material
- \( c \): Specific heat of the web material
- \( l \): Length of the coating zone
- \( v \): Web speed
Total heat transfer coefficient:

\[ k = k_{\text{contact}} + k_{\text{gas}} \]

\[ k_{\text{contact}} \leq 100 \text{ W/m}^2\text{/K} \]
\[ k_{\text{gas}} \sim \ldots 1000 \text{ W/m}^2\text{/K} \]

i.e. predominating effect in web coating processes caused by gas desorption induced gas cushion between web and coating drum

## Applications of metal foil coating

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<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>60 µm</td>
<td>Cu</td>
<td>... 30 µm</td>
<td>unknown</td>
</tr>
<tr>
<td>Cu</td>
<td>50 µm</td>
<td>Si</td>
<td>5 µm</td>
<td>unknown</td>
</tr>
<tr>
<td>Cu</td>
<td>50 µm</td>
<td>Ti</td>
<td>0,4 µm</td>
<td>unknown</td>
</tr>
<tr>
<td>Steel</td>
<td>100 µm</td>
<td>Al</td>
<td>8 µm</td>
<td>batteries</td>
</tr>
<tr>
<td>Steel</td>
<td>100 µm</td>
<td>Cu</td>
<td>3 µm</td>
<td>batteries</td>
</tr>
</tbody>
</table>
Temperature rise of metal foils by condensation heat load (without cooling)

- silicon on 0.05 mm copper
- aluminum on 0.1 mm steel
- copper on 0.1 mm steel
Temperature rise of copper foil on cooling drum for different heat transfer coefficients

substrate: copper foil with thickness 50 µm

![Graph showing temperature rise for different heat transfer coefficients](graph.png)
Temperature rise of metal foils by condensation heat load (with cooling drum)

- silicon on 0.05 mm copper
- aluminum on 0.1 mm steel
- copper on 0.1 mm steel

$k = 75 \text{ W/cm}^2/\text{K}$
EB evaporation arrangement of FOBA 600

- Dual Magnetron
- Cooling Drum
- Winding System
- EB-Gun
- Crucible System
High speed web coater FOBA 600
Web coater FOBA 600 – winding system

Winding system with copper foil of 50 µm thickness
Experimental investigations at FOBA 600

- **Aim:** Determination of heat transfer coefficient between substrate and cooling drum for metal foil coating process

- **Experimental conditions:**
  - Substrate: copper foil, thickness 50 µm
  - Process: EB - Ti coating
    - Evaporation from copper crucible
    - EB power ab. 50 kW
  - Temperature measurement of copper foil and additional uncooled test samples
Experimental investigations at FOBA 600

- Data interpretation:
  - Simulation of temperature measurements on copper strip by numerical solution of equation of heat balance, fit of heat transfer coefficient
  - Using of temperature measurements of uncooled test samples, special tests and layer thickness measurements for evaluation of fractions of substrate heat load
Temperature rise of copper foil (passing deposition area) and power density fractions fitted from experimental data: EB-PVD Ti layer 320 nm on copper foil 50µm

- Temperature difference
- Condensation heat load
- Thermal radiation
- Back scattered electrons

Before depos.

Distance to crucible center / cm

After depos.

Power density at substrate / W/cm²
Experimental investigations at FOBA 600

• Result:
  - Heat transfer coefficient $k_{\text{appr.}}$ 50 W/m$^2$/K between copper foil and cooling drum

• Interpretation:
  - Different outgassing behavior of metal foils compared to plastic web, especially with suitable pretreatment results in significantly reduced heat transfer coefficient $k_{\text{gas}}$
Conclusions

- Substrate thermal load can be a limiting factor in PVD processes.
- Thermal effects on substrates as plastic web or thin metal foils during deposition have to be considered in design of roll-to-roll coaters.
- Also in thin metal foil coating, especially during the deposition of layers in the range of some micrometers, the maximum allowed substrate temperature can be exceeded.
- Heat transfer coefficient between metal foil and cooling drum can be significantly less than in the case of plastic web coating.
High speed web coater FOBA 600