Sebastian März (Otto Junker, Lammersdorf)
Prof. Dr. Herbert Pfeifer (RWTH Aachen University, Department of Industrial Furnaces and Heat Engineering)

„Modern Furnaces for the Aluminium Industry „

Thursday, December 11st 2014
Process routes for the production of aluminium flat products based on secondary raw materials
**Table A2.2:** Heating- and hot forming temperatures for nonferrous metals [1]

<table>
<thead>
<tr>
<th>Nonferrous metals</th>
<th>Heating-temperature °C</th>
<th>Hot forming temperature at start °C</th>
<th>Hot forming temperature at end °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al and Al-alloys</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pure aluminium</td>
<td>500 to 570</td>
<td>480 to 550</td>
<td>340 to 360</td>
</tr>
<tr>
<td>Al-Mg-alloys (Al-Mg 3)</td>
<td>420 to 470</td>
<td>400 to 450</td>
<td>300 to 330</td>
</tr>
<tr>
<td>Al-Cu-Mg-alloys (AlCu4 Mg2)</td>
<td>500 to 540</td>
<td>480 to 520</td>
<td>340 to 360</td>
</tr>
<tr>
<td>Al-Mn-alloys (2 % Mn)</td>
<td>500 to 540</td>
<td>480 to 520</td>
<td>400 to 450</td>
</tr>
<tr>
<td>Al-Zn-Mg-Cr-alloys (AlZnMgCu0,5)</td>
<td>440 to 500</td>
<td>420 to 480</td>
<td>330 to 360</td>
</tr>
</tbody>
</table>

**Table A2.3:** Temperatures for the annealing of steels and nonferrous metals [1]

<table>
<thead>
<tr>
<th>Annealing process</th>
<th>Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aluminium and Al-alloys</strong></td>
<td></td>
</tr>
<tr>
<td>Homogenizing</td>
<td>460 to 580</td>
</tr>
<tr>
<td>(Solution annealing)</td>
<td></td>
</tr>
<tr>
<td>Stress-relief annealing</td>
<td>300 to 440</td>
</tr>
<tr>
<td>(Recrystallization annealing)</td>
<td></td>
</tr>
<tr>
<td>Recovery annealing</td>
<td>150 to 330</td>
</tr>
<tr>
<td>Artificial ageing</td>
<td>120 to 200</td>
</tr>
</tbody>
</table>
Table A2.5: Homogenizing temperatures for Al-alloys [2]

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Temperature range °C</th>
<th>Duration h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al 99.9</td>
<td>560 to 590</td>
<td>16 to 20</td>
</tr>
<tr>
<td>Al Mg2</td>
<td>460 to 500</td>
<td>10 to 15</td>
</tr>
<tr>
<td>Al Mg5</td>
<td>470 to 530</td>
<td>12 to 18</td>
</tr>
<tr>
<td>Al Mn1</td>
<td>590 to 630</td>
<td>6 to 9</td>
</tr>
<tr>
<td>Al MgSi0.5</td>
<td>500 to 580</td>
<td>6 to 8</td>
</tr>
<tr>
<td>Al Mg1Si</td>
<td>530 to 550</td>
<td>14 to 18</td>
</tr>
<tr>
<td>Al CuMg1</td>
<td>480 to 510</td>
<td>8 to 18</td>
</tr>
<tr>
<td>Al CuMg2Mn</td>
<td>470 to 490</td>
<td>12 to 20</td>
</tr>
<tr>
<td>Al ZnMgCu1.5</td>
<td>460 to 490</td>
<td>up to 13</td>
</tr>
<tr>
<td>Chemical symbol Prefix EN AW-</td>
<td>Solution annealing temperature °C</td>
<td>Cooling time to &lt;200 °C s</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-----------------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>Al Cu4MgSi(A)</td>
<td>500</td>
<td>5 to 10</td>
</tr>
<tr>
<td>Al Cu2.5Mg0.5</td>
<td>475 to 505</td>
<td>40 to 60</td>
</tr>
<tr>
<td>Al SiMgMn</td>
<td>540</td>
<td>20 to 30</td>
</tr>
<tr>
<td>EAl MgSi(B)</td>
<td>530</td>
<td>40 to 60</td>
</tr>
<tr>
<td>Al Zn4.5Mg1</td>
<td>450</td>
<td>5 to 20 min</td>
</tr>
<tr>
<td>Al Zn5.5MgCu(A)</td>
<td>530</td>
<td>30 to 40</td>
</tr>
</tbody>
</table>
Furnaces for the heat treatment of Al are dominated by convective heat transfer.

Convective heat transfer to rolling slabs, (a) impingement flow, (b) gap flow

Flow principles in reheating furnaces for Al slabs, (a) gap flow, (b) mass flow
Single nozzle

Round and flat nozzle fields
radiant tubes
Strahlheizröhren
furnace cover
Ofendeckel
Burner Fans
Brenner
Umluftventilatoren
Al-Pit furnace
Tieföfen
Al-pusher type furnace
Direct gas heated pusher-type furnace for pre-heating and homogenisation of Al-slabs
<table>
<thead>
<tr>
<th>Process step</th>
<th>User</th>
<th>Fuel consumption</th>
<th></th>
<th>Electrical energy consumption</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cold air burner</td>
<td>Recuperative burner</td>
<td>Cold air burner</td>
<td>Recuperative burner</td>
</tr>
<tr>
<td>Holding</td>
<td>Heat flow to load</td>
<td>7,825 kWh</td>
<td>7,825 kWh</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>Recirculating fan</td>
<td>-239 kWh</td>
<td>-239 kWh</td>
<td>266 kWh</td>
<td>266 kWh</td>
</tr>
<tr>
<td>Holding</td>
<td>Recirculating fan</td>
<td>-36 kWh</td>
<td>-36 kWh</td>
<td>40 kWh</td>
<td>40 kWh</td>
</tr>
<tr>
<td>Heating + holding</td>
<td>Heat flow to load</td>
<td>556 kWh</td>
<td>556 kWh</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td></td>
<td>Combustion air fan</td>
<td>-124 kWh</td>
<td>-103 kWh</td>
<td>138 kWh</td>
<td>115 kWh</td>
</tr>
<tr>
<td>Cooling</td>
<td>Recirculating fan</td>
<td>−</td>
<td>−</td>
<td>620 kWh</td>
<td>620 kWh</td>
</tr>
<tr>
<td>Heating + holding + cooling</td>
<td>Control unit</td>
<td>−</td>
<td>−</td>
<td>45 kWh</td>
<td>45 kWh</td>
</tr>
<tr>
<td>Net consumption</td>
<td></td>
<td>7,981 kWh</td>
<td>8,002 kWh</td>
<td>1,108 kWh</td>
<td>1,086 kWh</td>
</tr>
<tr>
<td>Gross consumption</td>
<td></td>
<td>11,241 kWh</td>
<td>9,414 kWh</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Spec. consumption related on load mass</td>
<td></td>
<td>245 kWh/t</td>
<td>205 kWh/t</td>
<td>24 kWh/t</td>
<td>24 kWh/t</td>
</tr>
</tbody>
</table>
Energy and material flows for the determination of the total energy input
Characteristic mass flows of combustion
Energy balances and system boundaries for an industrial furnace with air preheating
Air preheating in industrial furnaces

Centralized
- Radiation recuperator
- Convection recuperator

Decentralized
- Radiation/convection recuperator
- Recuperative burner
- Regenerative burner
Combustion efficiency

Fuel: CH₄

Temperature in °C

Combustion efficiency

Air

Oxyfuel

Air pre heating

800 °C

600 °C

400 °C

λ = 1.0

λ = 1.1

Process temperature

Adiabatic combustion temperature (λ = 1.1)
Advantage and characteristics of flameless oxidation

- Development and enhancement of fuel fired burners
  - main goal: increase of efficiency
  - use of high off-gas enthalpy for air preheating
  - challenge: Reduction of high NO\textsubscript{x}-emission

- FLOX\textsuperscript{®} - Combustion reaction without flame
  - high inlet velocity (> flame velocity)
  - recirculation of off-gas
  - increase of reacting volume
  - homogenization of temperature in reaction zone
  - no temperature maxima as in flame-front
  - significant decrease of NO\textsubscript{x}-emission
- flame operation mode for heat-up process
- (blue) stoichiometric gas flame
- power: 8 kW
NO\textsubscript{x}-Reduction in FLOX\textsuperscript{®} - operation mode ($T_{\text{reactor}} = 840 \, ^\circ\text{C}$)
Fluid-Structure-Interaction (FSI) in the field of industrial furnace engineering:

Simulation of fluid flow
- Energy
- Momentum
- Turbulence

Simulation of structure
- Thermal expansion
- Stress / Strain

1-Way Coupling: small deformations fluid flow structure
Total heat flux and temperature distribution

Heat flux in W/m²

Temperature in °C

≥ 45000
41250
37500
33750
30000
26250
22500
18750
15000
11250
7500
3750
0

≥ 620
798
775
753
730
708
685
663
640
618
595
573
≤ 550

insulation
Stresses on the radiant heating tube (1)

Intersection between insulation and furnace chamber

- high temperature gradient (approx. 100 K)
- high stresses
Stresses on the radiant heating tube (2)

Different temperatures between the arms of the radiant tube

\[ \Delta T \approx 20\ldots40 \text{ K} \]
Stress and strain as a function of circumference

![Graphs showing stress and strain as a function of circumference.](image)
Contribution of stresses on the radiant heating tube

- gravitation
- $\Delta T$ wall thickness
- $\Delta T$ internal side
- $\Delta T$ arms

Maximum stresses in MPa
Fans 4 x 90 kW
Radiant tubes 8 x 200 kW
Inner casing
Nozzle field
Sleeve
Coil
4 Zones
Volume flow measurement

- Fans: 4 x 90 kW
- Radiant tubes: 8 x 200 kW
- Inner casing
- Nozzle field
- Sleeve
- Coil
- 4 Zones
Deutliche Abweichungen zwischen Herstellerangaben (Normprüfstand) und Ofen/Versuchsstand

Ziel dieses Projektes: kontinuierliche Volumenstromerfassung als Standardmessung in Wärmebehandlungsöfen
Die Messpositionen des Messkreuzes wurden auf dem Radius $R_{MP} = 0,74 \cdot R_{ME}$ eingebracht.
Strömungsgeschwindigkeit in der Einlaufdüse als Funktion des Azimuts $\phi$ (Polarkoordinaten, $z = 80, r = 190$ mm)

<table>
<thead>
<tr>
<th>$\phi$ in °</th>
<th>$Re_{ed} \cdot 10^5$</th>
<th>$n_v$ in min$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0,274</td>
<td>9,38</td>
</tr>
<tr>
<td>2</td>
<td>0,188</td>
<td>6,44</td>
</tr>
<tr>
<td>3</td>
<td>0,075</td>
<td>2,65</td>
</tr>
<tr>
<td>4</td>
<td>0,054</td>
<td>1,85</td>
</tr>
<tr>
<td>5</td>
<td>0,188</td>
<td>9,38</td>
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Laufraddurchmesser: $D_2 = 650$ mm
$\varphi = k_v \cdot \frac{\dot{V}_v}{n_v}$

$R_{MP} = 0,74 \cdot R_{ME}$

$k_{MK} = \text{const} = 0,76$
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</table>
Casting up to 700 °C
PreHeat / Homogenization up to 550 °C
Strip Solutionizing up to 550 °C
Plate Solutionizing up to 550 °C
Stress Relief up to 550 °C
Homogenization up to 550 °C
Interm. Anneal up to 550 °C
Final. Anneal up to 550 °C
Technology Today

- **Coil Annealing Furnaces for Intermediate or Temper Annealing of rolled aluminium coils**

- **Discontinous process:**
  - Compiling the batch
  - Feeding the Furnace, Start of Heat Treatment
  - Heat Treatment
  - End of Heat Treatment – Remove the Batch
Heat Treatment Process

- ...either according to pre determined receipe (Temperature/Time/Fanspeed)
- Or according to measured metal temperature
Mathematical model for increase of energy efficiency

• Energy demand and CO$_2$ emission of coil annealing furnaces

  • Reference: aluminium, 20-420°C, energy demand: 185 kWh$_{\text{th}}$/t and 28 kWh$_{\text{el}}$/t, respectively

  • At an annual output of 1.8 million tonnes of flat products, at least 100,000 tonnes of CO$_2$ are released for intermediate and final annealing purposes in Germany alone.

  • The need to purchase CO$_2$ emission rights is to be anticipated as of 2013

Reason enough to start examining the use of saving potentials as early as today!
An Aluminium Coil ....

...looks like a big solid block

A microscopical view shows ...
Heat up physics for strip coils

That a coil consists of hundreds of layers of Aluminium strip and hundreds of layers of oil and air which have an insulating effect, so that only 5 - 10% of heat input takes place via the circumference.

90 - 95% of heat input takes place via the face ends.
Heat up physics for strip coils

High convection heating from the face ends is more efficient than mass flow around the circumference.
Mathematical model for increase of energy efficiency

• Concept of mathematical modelling

Production planning
• puts together most suitable charge lots from stock in “offline” mode

Interfacing
• optimizes production planning by introducing empirical process management data

Process management
• computes metal temperatures “online” and controls influencing process parameters
Architektur

- Lagerbestand Bandbunde
- energie- oder zeitoptimierte Chargen
- Charge SOLL (Beladung, Rezept)
- Charge IST (Zeiten, Temperaturen)
- Empirische Daten
- Prozessparameter SOLL
- Prozessparameter IST
- Visualisierung
- Bedienung

Modellrechner “offline”

Modellrechner “online”

PDM

MMI

SPS
Mathematisches Modell: e) Ergebnisse

Über $n=50$ Chargen wurde eine Genauigkeit von besser als 1% der Zieltemperatur reproduzierbar erreicht.
Mathematical model for increase of energy efficiency

- Operating experience:

In foil annealing, the mathematical model developed by OTTO JUNKER equalizes a 50K temperature difference to ± 3 K.
Mathematical model for increase of energy efficiency

- **Estimate of potential CO₂ savings**
- \(\frac{2}{3}\) from fuel savings, \(\frac{1}{3}\) from reduced electrical power demand

![Graph showing carbon dioxide saving in mt/yr against increase of average entry temperature in K for different production rates.](image-url)
- Possible Materials

- 2xxx Al-Cu
- 6xxx Al-Mg-Si
- 7xxx Al-Zn-Mg

![Diagram showing possible materials and their behavior at higher temperature with larger percentage of alloying element.](image-url)
- Complete Cycle (3 steps)
- Complete Cycle (3 steps)

- Heating
- Complete Cycle (3 steps)
  - Heating
  - Quenching
- Complete Cycle (3 steps)
  - Heating
  - Quenching
  - Aging
How to prevent alloying element from segregation?
How to prevent alloying element from segregation?

...... being fast enough
- Speed matters
- Speed matters

![Graph showing temperature change over time with a note on slow cooling.](image-url)
- Speed matters

![Graph showing the relationship between time and temperature, with fast cooling and slow cooling highlighted.](image-url)
- Speed matters – as fast as necessary…

Avoid that line to prevent segregation
- Speed matters – as fast as necessary - but as slow as possible
Different Alloys – Different Requirements

- 7075
■ Different Alloys – Different Requirements
Different Alloys – Different Requirements
Different Alloys – Different Requirements
Different Alloys – Different Requirements
- Strip Flotation Line

- Min Gauge 0.3 mm
- Max Gauge 4 mm
- Min cooling rate: ~ 30 K/s
- Max cooling rate: > 300 K/s
- Alpha

- Alpha ($\alpha$) = Heat Transfer Coefficient

- $\alpha \sim v^{0.7}$ [W/m²K]

- Determines how much heat is transferred per each m² of (contact) surface and temperature difference (Medium to metal)
- The higher the alpha value – the higher the cooling rate
The thicker the strip, the lower the cooling rate (with given alpha value)
Faster Cooling (K/s)

Higher Alpha (W/m²K)

- 0.3 mm
- 0.5 mm
- 1.5 mm
- 4 mm
Faster Cooling (K/s)

Higher Alpha (W/m²K)

- 0.3 mm
- 0.5 mm
- 1 mm
- 1.5 mm
- 2 mm
- 2.5 mm
- 3 mm
- 4 mm
- Strip Flotation Line

- Min Gauge 0.3 mm
- Max Gauge 4 mm
- Min cooling rate: ~ 30 K/s
- Max cooling rate: > 300 K/s
Faster Cooling (K/s)

Thicker Strip (mm)

$\alpha = 5.800 \text{ W/m}^2\text{K}$
- **Water Cooling**
  \[ \alpha \sim 5.800 - 1.800 \text{ W/m}^2\text{K} \]
Faster Cooling (K/s)

Thicker Strip (mm)

Hardquench

Aircooling
Otto Junker Mist Quench
- **Water Cooling**
  \[ \alpha \approx 5.800 \text{ – } 1800 \text{ W/m}^2\text{K} \]

- **Air Cooling**
  \[ \alpha \approx 40 \text{ – } 180 \text{ W/m}^2\text{K} \]
- Water Injected into Air Stream
- $\alpha$ function of air speed
- $\alpha$ function of water density
- $\alpha$ function of air speed
- $\alpha$ function of water density
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