ALUNORD
Week 41, 2009
CONSTRUCTION in ALUMINIUM – Part I
by Anders Kristensen
Program

• The design process
• Structural design issues
• Example – helideck support structure
• Example – luggage lift
• Example – simulation
A good idea!
Product Development Stages

- Idea generation
- Assessment of firm’s ability to carry out
- Customer Requirements
- Functional Specification
- ProductSpecifications
- Design Review
- Test Market
- Introduction to Market
- Evaluation

Scope of design for manufacturability and value engineering teams

ALUNORD 2009, Esbjerg
Design considerations and structural analysis
Issues for Product Development

• Robust design
• Time-based competition
• Modular design
• Computer-aided design
• Value analysis
• Environmentally friendly design
Strategy and Issues During a Product’s Life

**Company Strategy/Issues**
- Best period to increase market share
- R&D engineering is critical
- Sales
- Flat-screen monitors

**OM Strategy/Issues**
- Product design and development critical
- Frequent product and process design changes
- Short production runs
- High production costs
- Limited models
- Attention to quality

**Introduction**
- Practical to change price or quality image
- Strengthen niche

**Growth**
- Drive-thru restaurants
- CD-ROM
- Internet
- Color printers
- DVD

**Maturity**
- Fax machines
- 3 1/2” Floppy disks

**Decline**
- Cost control critical

- Forecasting critical
- Product and process reliability
- Competitive product improvements and options
- Increase capacity
- Shift toward product focus
- Enhance distribution

- Standardization
- Less rapid product changes—more minor changes
- Optimum capacity
- Increasing stability of process
- Long production runs
- Product improvement and cost cutting

- Little product differentiation
- Cost minimization
- Overcapacity in the industry
- Prune line to eliminate items not returning good margin
- Reduce capacity

**Design considerations and structural analysis**
Improving The Design Process: Design For Manufacture (DFM)

• Design a product for easy & economical production
• Consider manufacturability early in the design phase
• Identify easy-to-manufacture product-design characteristics
• Use easy to fabricate & assemble components
• Integrate product design with process planning
DFM Guidelines

1. Minimize the number of parts
2. Develop a modular design
3. Design parts for multi-use
4. Avoid separate fasteners
5. Eliminate adjustments
6. Design for top-down assembly
7. Design for minimum handling
8. Avoid tools
DFM Guidelines (continued)

9. Minimize subassemblies
10. Use standard parts when possible
11. Simplify operations
12. Design for efficient and adequate testing
13. Use repeatable & understood processes
14. Analyze failures
15. Rigorously assess value
Structural design issues

- Some design considerations:
  - Structural design criteria – failure modes
  - Stress concentration – notch sensitivity
  - Buckling/instability – modal analysis
  - Eigen-frequency – modal analysis
  - Contact with dissimilar metals
  - Welding and temperature affect mechanical properties
  - Corrosion
  - Fatigue considerations:
    - No endurance limit for Aluminum in S-N diagram
    - Consider fracture toughness properties for the material
Failure Modes

- **Deformation**
  - Modulus of Elasticity (E [MPa])
  - Moment of inertia

- **Yielding**
  - Yielding Stress (Re [MPa])
  - Modulus of Elasticity (E [MPa])

- **Ductile rupture**
  - Yielding Stress (Re [MPa])
  - Modulus of Elasticity (E [MPa])

- **Brittle fracture**
  - Ultimate Tensile Stress (Rm [MPa])
  - Modulus of Elasticity (E [MPa])

- **Fatigue**
  - Endurance limit
  - Design approach, e.g. Fail-safe, Damage Tolerant
  - Fracture toughness

- **Corrosion**
- **Wear**
- **Impact**
- **Creep**
- **Buckling**
  - Moment of inertia
  - Modulus of Elasticity (E [MPa])

- **Stress corrosion (synergistic)**
# Mechanical Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield Stress (MPa)</th>
<th>Ultimate Stress (MPa)</th>
<th>Ductility EL%</th>
<th>Elastic Modulus (MPa)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1040 Steel</td>
<td>350</td>
<td>520</td>
<td>30</td>
<td>207000</td>
<td>0.30</td>
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<tr>
<td>1080 Steel</td>
<td>380</td>
<td>615</td>
<td>25</td>
<td>207000</td>
<td>0.30</td>
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<tr>
<td>2024 Al Alloy</td>
<td>100</td>
<td>200</td>
<td>18</td>
<td>72000</td>
<td>0.33</td>
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<tr>
<td>316 Stainless Steel</td>
<td>210</td>
<td>550</td>
<td>60</td>
<td>195000</td>
<td>0.30</td>
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<td>70/30 Brass</td>
<td>75</td>
<td>300</td>
<td>70</td>
<td>110000</td>
<td>0.35</td>
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<td>6-4 Ti Alloy</td>
<td>942</td>
<td>1000</td>
<td>14</td>
<td>107000</td>
<td>0.36</td>
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<tr>
<td>AZ80 Mg Alloy</td>
<td>285</td>
<td>340</td>
<td>11</td>
<td>45000</td>
<td>0.29</td>
</tr>
</tbody>
</table>
## Mechanical Properties

**Table 4.5 Mechanical properties of 357 aluminium alloy produced by different casting processes (from Lavington, M. H., Metals and Materials, 2, 713, 1986)**

<table>
<thead>
<tr>
<th>Process</th>
<th>0.2% proof stress MPa</th>
<th>Tensile strength MPa</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand cast</td>
<td>200</td>
<td>226</td>
<td>1.6</td>
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<tr>
<td>Chill cast</td>
<td>248</td>
<td>319</td>
<td>6.9</td>
</tr>
<tr>
<td>Squeeze cast</td>
<td>293</td>
<td>347</td>
<td>9.3</td>
</tr>
<tr>
<td>Cosworth</td>
<td>242</td>
<td>312</td>
<td>9.8</td>
</tr>
</tbody>
</table>
Design criteria

Hamrock, Fig. 6-17
Stress concentration – notch sensitivity

![Diagram of a stress concentration notch](image)

![Graph showing notch sensitivity](image)
Load, $P$

EIGEN BUCKLING

$$P_{cr} = \frac{\pi^2 EI}{(L_e)^2}$$

$I = 2$nd Moment of Area about weak axis.

$E = \text{Young's Modulus}$
The effective length, $L_e$, depends on the **Boundary Conditions**:

<table>
<thead>
<tr>
<th>Theoretical</th>
<th>$L_e = L$</th>
<th>$L_e = 0.707L$</th>
<th>$L_e = 0.5L$</th>
<th>$L_e = L$</th>
<th>$L_e = 2L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum AISC Recommend</td>
<td>$L_e = L$</td>
<td>$L_e = 0.80L$</td>
<td>$L_e = 0.65L$</td>
<td>$L_e = 1.2L$</td>
<td>$L_e = 2.1L$</td>
</tr>
</tbody>
</table>
Find the **Buckling load** for a pin-ended aluminum column 3m high, with a rectangular x-section as shown:

**Weak axis:**

\[ I_{yy} = \frac{100 (50)^3}{12} = 1.04 \times 10^6 \text{ mm}^4 \]

\[
P_{cr} = \frac{\pi^2 (72000)(1.04 \times 10^6)}{(3000)^2}
\]

\[ = 82246 \text{ N} \]
Dynamic Effects

Static, i.e. acceleration $\approx 0$

$$KD = F$$

Dynamic, i.e. acceleration $\neq 0$

$$M\ddot{D} + C\dot{D} + KD = F$$

- Inertia force – mass times acceleration
- Damping force – damping times velocity
- Elastic Force – stiffness times deformation
- External force
- Dynamic Effects

$$[k] = \begin{bmatrix}
\frac{12EI}{L^3} & \frac{6EI}{L^2} & \frac{-12EI}{L^3} & \frac{6EI}{L^2} \\
\frac{6EI}{L^2} & \frac{4EI}{L} & \frac{-6EI}{L^2} & \frac{2EI}{L} \\
\frac{-12EI}{L^3} & \frac{-6EI}{L^2} & \frac{12EI}{L^3} & \frac{-6EI}{L^2} \\
\frac{6EI}{L^2} & \frac{2EI}{L} & \frac{-6EI}{L^2} & \frac{4EI}{L}
\end{bmatrix}$$
Modal Analysis

• Avoid resonance
• Exploit resonance
• Assess structural stiffness
• Structural modal degrees of freedom
• Further dynamic analyses
• etc.
# Contact with dissimilar metals

## Table 2.3 Electrode potentials of various metals and alloys with respect to the 0.1 M calomel electrode in aqueous solutions of 53 g l⁻¹ NaCl and 3 g l⁻¹ H₂O₂ at 25°C (from Metals Handbook, Volume 1, American Society for Metals, Cleveland, Ohio, 1961)

<table>
<thead>
<tr>
<th>Metal or alloy</th>
<th>Potential (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium</td>
<td>-1.73</td>
</tr>
<tr>
<td>Zinc</td>
<td>-1.10</td>
</tr>
<tr>
<td>Alclad 6061, Alclad 7079</td>
<td>-0.89</td>
</tr>
<tr>
<td>5056, 5056</td>
<td>-0.87</td>
</tr>
<tr>
<td>Aluminium (99.95%), 5056, 5086</td>
<td>-0.85</td>
</tr>
<tr>
<td>2004, 1060, 5050</td>
<td>-0.84</td>
</tr>
<tr>
<td>1100, 3003, 6063, 6061, Alclad 2024</td>
<td>-0.83</td>
</tr>
<tr>
<td>9004-T4</td>
<td>-0.69</td>
</tr>
<tr>
<td>Cadmium</td>
<td>-0.82</td>
</tr>
<tr>
<td>Mild steel</td>
<td>-0.68</td>
</tr>
<tr>
<td>Lead</td>
<td>-0.55</td>
</tr>
<tr>
<td>Tin</td>
<td>-0.49</td>
</tr>
<tr>
<td>Copper</td>
<td>-0.20</td>
</tr>
<tr>
<td>Stainless steel (3xx series)</td>
<td>-0.09</td>
</tr>
<tr>
<td>Nickel</td>
<td>-0.07</td>
</tr>
<tr>
<td>Chromium</td>
<td>-0.49 to +0.18</td>
</tr>
</tbody>
</table>

* Compositions corresponding to the numbers are given in Tables 3.2 and 3.4

## Table 2.4 Electrode potentials of aluminum solid solutions and micro-constituents with respect to the 0.1 M calomel electrode in aqueous solutions of 53 g l⁻¹ NaCl and 3 g l⁻¹ H₂O₂ at 25°C (from Metals Handbook, Volume 1, American Society for Metals, Cleveland, Ohio, 1961)

<table>
<thead>
<tr>
<th>Solid solution or micro-constituent</th>
<th>Potential (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg₃Al₈</td>
<td>-1.24</td>
</tr>
<tr>
<td>Al-Zn-Mg solid solution (1% MgZn₂)</td>
<td>-1.07</td>
</tr>
<tr>
<td>MgZn₂</td>
<td>-1.05</td>
</tr>
<tr>
<td>Al₂CuMg</td>
<td>-1.00</td>
</tr>
<tr>
<td>Al-5% Mg solid solution</td>
<td>-0.58</td>
</tr>
<tr>
<td>MnAl₃</td>
<td>-0.85</td>
</tr>
<tr>
<td>Aluminium (99.95%)</td>
<td>-0.85</td>
</tr>
<tr>
<td>Al-Mg-Si solid solution (1% Mg₃Si)</td>
<td>-0.83</td>
</tr>
<tr>
<td>Al-1% Si solid solution</td>
<td>-0.81</td>
</tr>
<tr>
<td>Al-2% Cu supersaturated solid solution</td>
<td>-0.75</td>
</tr>
<tr>
<td>Al-4% Cu supersaturated solid solution</td>
<td>-0.69</td>
</tr>
<tr>
<td>FeAl₃</td>
<td>-0.55</td>
</tr>
<tr>
<td>CuAl₂</td>
<td>-0.53</td>
</tr>
<tr>
<td>NiAl₃</td>
<td>-0.52</td>
</tr>
<tr>
<td>Si</td>
<td>-0.25</td>
</tr>
</tbody>
</table>
Contact with dissimilar metals

More prone to corrosion

Aluminium
Steel

Improved

Insulation
Aluminium
Steel

Unacceptable

Aluminium
Steel

Acceptable

Aluminium
Insulation
Steel

Deck plank

M20 Bolts
ss316 w/ Insulation

Aluminium girder
2 mm neoprene sheet

Weld

Support structure

20 mm steel plate

http://www.kappaluminium.no/
Welding

• If the base material has been cold worked prior to welding, the effect of work hardening is completely gone in the fusion zone due to remelting and is partially lost in HAZ due to recrystallisation and grain growth.

• Note: Strength loss should be taken into account in structural designs. (even Toughness) The harder the base metal, the greater the strength loss is.

Softening of workhardened Material caused by welding
(a) thermal cycles
(b) strength or Fusion hardness profile.
Corrosion

• Constructive prevention of corrosion is the most inexpensive and the most effective.
Corrosion
Fatigue considerations

- Aluminum alloys
  - $S_e$ ($S$, at $10^6$ cycles)
    - $= 0.4 S_{ut}$ for $S_{ut} < 330$ MPa
    - $= 130$ MPa for all other values of $S_{ut}$

**Figure 12-3** Typical fatigue curves for ferrous and nonferrous metals.
Fatigue considerations

- Toughness is resistance of material to fracture (in the presence of cracks).

- Crack extension is due to nucleation of crack by decohesion at second phase particle-matrix interface.

- Toughness is greatest in underaged condition and decrease as ageing proceeds to peak strength.

- Note: Reducing Fe and Si (impurities) greatly improves the toughness.
Fatigue considerations

- The improvement in tensile strength is not always accompanied with increased fatigue strength in non-ferrous alloys.
- The more an alloy is dependent upon precipitation-hardening for its tensile strength, the lower its fatigue ratio (endurance limit : tensile strength) becomes.
- Age-hardened aluminium alloys possess disappointing fatigue properties due to localised straining of precipitates under cyclic stressing. Improved by more uniformly dispersed precipitates to prevent coarse slips formation.
- An increase in dislocation density by thermo mechanical processing helps to improve fatigue performance.
Microstructure-Fatigue Relationships

• Three major factors.
  1: geometry of the specimen (previous slide); anything on the surface that is a site of stress concentration will promote crack formation (shorten the time required for nucleation of cracks).

  2: defects in the material; anything inside the material that can reduce the stress and/or strain required to nucleate a crack (shorten the time required for nucleation of cracks).

  3: dislocation slip characteristics; if dislocation glide is confined to particular slip planes (called planar slip) then dislocations can pile up at any grain boundary or phase boundary. The head of the pile-up is a stress concentration which can initiate a crack.
Casting porosity affects fatigue

Gravity cast versus squeeze cast versus wrought Al-7010

- Casting tends to result in porosity. *Pores are effective sites for nucleation of fatigue cracks.* Castings thus tend to have lower fatigue resistance (as measured by S-N curves) than wrought materials.
- Casting technologies, such as *squeeze casting*, that reduce porosity tend to eliminate this difference.

*Fig. 4.9 Fatigue (S/N) curves for alloy 7010 in wrought, gravity diecast and squeeze-cast conditions (from Chadwick, G. A., *Metals and Materials*, 2, 693, 1986)*
A material property chart displaying the fatigue threshold stress intensity ($\Delta K_{th}$, obtained at $R = 0$) vs. endurance limit ($\sigma_e$, appropriate for $R = -1$). Although these two properties correlate for the several material classes, there are some subtleties. Ceramics, for example, have relatively high values of the ratio $\sigma_e/\Delta K_{th}$. Thus, they are more prone to crack-growth-limited fatigue fracture (extrinsic fatigue, cf. Fig. 12.21). Conversely, materials having high values of $\Delta K_{th}$ vis-à-vis $\sigma_e$ (e.g., some of the tough metals) are more prone to intrinsic fatigue, which involves nucleation of the fatigue cracks that result in fracture (also see Fig. 12.21). (Adapted from N. A. Fleck, K. J. Kang, and M. F. Ashby, “The Cyclic Properties of Engineering Materials,” Acta Metall. et Mater., 42, 365, Copyright 1994, with permission from Elsevier Science.)
Example – Helideck support structure

http://aluminium-offshore.com/
Example – Helideck support structure

Aluminium
EN AW 6082-T6
AlSi1MgMn alloy

Steel
EN 10 025 S355 K2 G3
Mn, Si, P, S alloying elements
Example – Helideck support structure

**Aluminium**
- Welding reduce strength in HAZ up to 30-50% and it is difficult to improve
- Inspection is required (NDT)
- SCF, i.e. welding and geometrical sharp edges (notches) increase the stress level significantly
- Price
  - Can be increased by introducing welding, i.e. increased requirements to inspection
- Weight
  - Depends on the structural behaviour – in this case the use of bolts provide a very effective load-carrying structure
  - Resulting weight = 12000kg
- Serviceability
  - Easier to transport
- Manufacturability
  - No additional corrosion considerations
- Resale

**Steel**
- Welding require special considerations in respect to HAZ
- Inspection is required (NDT)
- SCF, i.e. welding and geometrical sharp edges (notches) increase the stress level significantly
- Price
  - Can be increased by introducing welding, i.e. increased requirements to inspection
- Weight
  - Depends on the structural behaviour – in this case the use of cylindrical members provide a very effective load-carrying structure
  - Resulting weight = 24000kg
- Serviceability
  - Structural analysis on base structure required
- Manufacturability
  - Require additional corrosion considerations
- Resale
Example – Helideck support structure

<table>
<thead>
<tr>
<th>Materiale</th>
<th>Al 6082 T4</th>
<th>S355JR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flydespænding, $\sigma_{\text{flyde}}$ [MPa]</td>
<td>162</td>
<td>355</td>
</tr>
<tr>
<td>Brudspænding, $\sigma_{\text{brud}}$ [MPa]</td>
<td>247</td>
<td>500</td>
</tr>
<tr>
<td>Elasticitetsmodul, $E$ [MPa]</td>
<td>70.000</td>
<td>210.000</td>
</tr>
<tr>
<td>Densitet, $\rho$ [kg/m$^3$]</td>
<td>2.700</td>
<td>7.850</td>
</tr>
<tr>
<td>Pris [$/\text{ton}]$</td>
<td>1.120</td>
<td>335</td>
</tr>
</tbody>
</table>

**TABLE 4 - Charpy impact test data, estimated yield strength and calculated fracture toughness values**

<table>
<thead>
<tr>
<th>Samples</th>
<th>Notch location</th>
<th>Charpy V impact data (average)</th>
<th>Vickers hardness (average)</th>
<th>Estimated yield strength</th>
<th>Estimated Fracture toughness $K_{\text{IC}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1..6 (unwelded)</td>
<td>Base material</td>
<td>10.6</td>
<td>100</td>
<td>242</td>
<td>32.5</td>
</tr>
<tr>
<td>7..12 (welded)</td>
<td>WM</td>
<td>6.9</td>
<td>60</td>
<td>132</td>
<td>20.2</td>
</tr>
<tr>
<td>13..18 (welded)</td>
<td>HAZ</td>
<td>13.0</td>
<td>70</td>
<td>162</td>
<td>32.9</td>
</tr>
</tbody>
</table>

(*) Estimated using the regression formula (2)
(**) Calculated from empirical relation (1)
Example – Helideck support structure

Stress-strain curve for aluminium and construction steel.

- Aluminium: E = 70 GPa
- Construction steel: E = 210 GPa

σ

σ_m

σ_e

ε

E = 70 GPa

E = 210 GPa
Example – Luggage lift
Example – Luggage lift
Example – Luggage lift
Mounting of lift
Timecycle
Operation cycle
Other opportunities

• Elderly/disabled
Freight
Material selection

- Design check of structural components
- Critical areas
- Manufacturing
Loading area

- Material – aluminium chosen
- Profil chosen (area moment of inertia)
- Wear
- Coating on rail
Liftarm

- Material – aluminium chosen
- No wear
- Designed as a structural loadcarrying member
Vertical rail

- Material – steel chosen
- Critical loads
- Weight
Critical issues

- Critical points
- Unusual load case
- Inclined lift
- Inclination
- Overload
Safety

- Safety
- Emergency stop
- Shielding
### Design phase

<table>
<thead>
<tr>
<th>Vægtning (1-10) [V]</th>
<th>10</th>
<th>8</th>
<th>7</th>
<th>5</th>
<th>3</th>
<th>2</th>
<th>10</th>
<th>7</th>
<th>7</th>
<th>6</th>
<th>P X V</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>30</td>
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<tr>
<td><strong>Design 2</strong></td>
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<td></td>
<td></td>
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<td>70</td>
<td>48</td>
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<tr>
<td><strong>Design 3</strong></td>
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<td>80</td>
<td>40</td>
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<td><strong>Design 4</strong></td>
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<td>40</td>
<td>16</td>
<td>14</td>
<td>10</td>
<td>216056356</td>
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<tr>
<td><strong>Design 5</strong></td>
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<td>60</td>
<td>48</td>
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<td>30</td>
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<td><strong>Design 6</strong></td>
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<td>56</td>
<td>56</td>
<td>40</td>
<td>211270493548</td>
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<tr>
<td><strong>Design 7</strong></td>
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<td></td>
<td></td>
<td>50</td>
<td>48</td>
<td>21</td>
<td>30</td>
<td>241450353548</td>
</tr>
</tbody>
</table>

Eksempelvis 8 point, vil give 470 i alt. Vil bevirke at design 6 ikke ligger alene i spidsen.

Eksempelvis 3 point, vil give 491 i alt.
Comments to the design phase

It is still possible to lay down the back seats
Example - simulation
Mechanical Properties

http://www.sasak.dk/
THANK YOU FOR YOUR ATTENTION