Introduction to Aerospace Engineering

Lecture slides
13

Materials
Contents

3 main topics:

- What are MATERIALS?

- OVERVIEW of materials

- Relationship
  - MATERIAL
  - DESIGN/STRUCTURE
  - MANUFACTURING?
What is a MATERIAL?

Could you give a brief definition? Features?

- Approximated by: “Substances” and “matter”
- Having specific properties, but without shape
Relation “structures” and “materials”

Structures are made of these “substances”, these materials. **How?**
OVERVIEW of materials

Most important materials for Aerospace applications:

- Metal alloys
- Composites
  
  Composed materials (fibers, resin, metal)

  Structurally not relevant

- Pure polymers: properties not good enough (strength, stiffness, etc.)
- Ceramics: too brittle
What are the names of the processes for Al and Fe?

Electrolysis (Al) and Blast Furnaces (Fe)
Metals & metal alloys

**Characteristics:**
- Isotropic *(what does it mean?)*
- Metal to be strengthened (alloying, heat treatment)
- *Plastic behavior* & Melting (recycling, welding)
- Good processibility
- Low costs (often)
**Metals and Metal alloys**

Huge diversity in (tension) properties

*(why stresses & strains)*

<table>
<thead>
<tr>
<th>Metal (alloy)</th>
<th>Density [kg/dm³]</th>
<th>spec. E-modulus</th>
<th>spec. yield strength</th>
<th>spec. Fail. strength</th>
<th>Maximum strain [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon steel (Norm.)</td>
<td>7.8</td>
<td>26.5</td>
<td>48</td>
<td>76</td>
<td>28</td>
</tr>
<tr>
<td>HS Steel (OQ-Temp)</td>
<td>7.8</td>
<td>26.5</td>
<td>208</td>
<td>226</td>
<td>12</td>
</tr>
<tr>
<td>pure Aluminum (O)</td>
<td>2.7</td>
<td>25.5</td>
<td>13</td>
<td>33</td>
<td>40</td>
</tr>
<tr>
<td>Al-2024-alloy (T351)</td>
<td>2.8</td>
<td>25.7</td>
<td>116</td>
<td>168</td>
<td>20</td>
</tr>
<tr>
<td>Al-7075-alloy (T6)</td>
<td>2.8</td>
<td>25.3</td>
<td>180</td>
<td>204</td>
<td>11</td>
</tr>
<tr>
<td>pure Titanium (An.)</td>
<td>4.5</td>
<td>22.9</td>
<td>38</td>
<td>53</td>
<td>30</td>
</tr>
<tr>
<td>Ti-6Al-4V alloy (An)</td>
<td>4.5</td>
<td>25.3</td>
<td>184</td>
<td>200</td>
<td>14</td>
</tr>
</tbody>
</table>

Specific: in this case (property/density - e.g. E/ρ - applicable for tension only!) **Why Specific?**
Polymers

As pure materials: Structurally not interesting

Macro-molecular substances
Two major types: thermoplastic and thermoset polymers
  • Thermoplastics: softening reversible, one component
  • Thermoset: curing irreversible, often more components
Polymers

**Characteristics:**
- Isotropic
- Low strength & stiffness
- Huge variety
- *Plastic flow* & Melting (recycling, welding)
- Good processibility
- Low costs (often)
Composites

*Fiber reinforced polymers*
- Polymers + fibers
- Fibers: glass, carbon, aramid, Dyneema
- Short, long, “continuous” fibers

*Hybrid materials:*
- GLARE: composite- and metal layers
Composites (examples)
Composites

Principles of composite materials ("continuous" fibers)

fibers (strong & stiff) embedded in resin (support & protect)
fibers: strong and stiff in one direction only!
anisotropic (direction dependent) behavior

Continuous fibers in resin

Layers (laminate)
Composites (cont.)

Features:

- Anisotropic (orientation) – *Benefit? When?*
- Layered structure (laminate)
- High strength & stiffness
- Low density but often costly
- No plasticity
- Good processibility
  - Prepregs
  - Draping in moulds - curing
Composites

Composite structures made of **laminates** – shell structure
thin-walled **sandwich**
- two laminates – facings
- lightweight core
Composites - sandwiches
Boeing 787

New Aircraft

Material – more than 50% composites
Composites in primary structures
Boeing 787

Shell structures
Polymers & composites and Metal alloys

Also a huge diversity in (tension) properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Density [kg/dm$^3$]</th>
<th>E-modulus [kN/mm$^2$]</th>
<th>yield strength [N/mm$^2$]</th>
<th>Failure strength [N/mm$^2$]</th>
<th>Maximum strain [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy (TS)</td>
<td>1.25</td>
<td>1.9</td>
<td>48</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>Polyetheretherketone (PEEK) (TP)</td>
<td>1.31</td>
<td>0.8</td>
<td>69</td>
<td>76</td>
<td>75</td>
</tr>
<tr>
<td>Polypropene (PP)</td>
<td>0.91</td>
<td>1.5</td>
<td>38</td>
<td>42</td>
<td>300</td>
</tr>
<tr>
<td>E-glass epoxy UD-60%</td>
<td>2.1</td>
<td>21</td>
<td>116</td>
<td>470</td>
<td>20</td>
</tr>
<tr>
<td>HM carbon epoxy UD 60%</td>
<td>1.7</td>
<td>129</td>
<td>200</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Al-2024-alloy (T351)</td>
<td>2.8</td>
<td>25.7</td>
<td>168</td>
<td>20</td>
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<tr>
<td>Ti-6Al-4V alloy (An)</td>
<td>4.5</td>
<td>25.3</td>
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Specific: in this case (property/density - e.g. E/$\rho$ - applicable for tension only!)
Space Materials

Have to fulfill *special requirements*
- High temperature loading
- Specific atmospheres (Oxygen, radiation, chemical reactions – i.c.w. high T)

\[ q_{aero} = q_{rad} + q_{con} \]

Will be continued
Link between Materials & Structures

Load carrying capacity of a structure depends on:

- Design, shape
- **Materials**
- Production techniques

*Examples?*

Note: Not every random combination (D, M, P) is possible! - There is interaction!!

*Examples?*
Materials – DESIGN & MANUFACTURE

Manufacturing techniques
- Casting
- Machining
- Forming
- Forging
- Joining

Materials
- Metal alloys
- Polymers
- Fiber-reinforced polymers
- Ceramics
- Hybrid materials

Performance (concept)

Design/shape
- Structural level
  - Tubes and truss structures
  - (stiffened) skin structure
  - Sandwich structure

- Part level
  - Flat
  - Single curved
  - Double curved
Metals - Manufacturing

- Liquid: Casting
- Solid High temperature: Forging
- Solid Room temperature: Forming (sheet); machining.
- Assembly - joining
Metals - casting

Solid $\Leftrightarrow$ Liquid

Injection molding
Metals - machining

Solid - cutting
Metals – forming

Sheet
Metals - joining

- felzen
- inbedden
- ingieten
- kitten
- klemmen
- klikverbinden
- klinken
- krimpen
- lassen
- lijmen
- lipverbinden
- nieten
- persen
- schroeven
- solderen
Composites – Lay-up and curing
Composites – forming
press forming

“Black” Metal??
Composites – filament winding/tape laying
Summary: composites vs. metal

Different Properties

**Metals**
+ Plastic behavior – damage tolerant - joining
+ Cheap materials – easy processing
  - Labor intensive

**Composites**
+ High spec. strength & stiffness *(specific?)* – low weight
+ High integration possible
  - Expensive materials → compensated by production
Summary: composites vs. metal

- **Different manufacturing** techniques
  - Laminating, filament winding (composites)
  - Plastic deformation, forging, casting (metals)
- **Different designs**
  - Sandwich (composites)
  - Stiffened shell structure (metal)
14.

Exploring the limits
Contents

X-planes

Flight regimes: From subsonic to hypersonic

High Temperature Materials
X-planes: Exploring the limits

X-plane – “X” stands for eXperimental

1st was Bell X1
Objective:
    fly supersonic
    sound “barrier”

Charles “Chuck” Yeager
October 14, 1947
1078 km/h (M = 1,015)
X-planes

A large number of experimental planes followed (see en.wikipedia.org/wiki/X-plane for complete overview)

Latest is the X-53

Main purpose for X-planes:
  Test specific features, phenomena, etc.
  e.g. scramjet, reentry from space, supersonic and hypersonic speeds, tailless aircraft
X-planes

Risky business: many test pilots died

In general only a few aircraft were build of a type
Number of flights was also very limited

E.g. Bell X-1A and 1B;
flew in 1953/54
Speed exceeding Mach 2;
15 and 27 flight resp.
X-planes

Few typical examples: X-15 (1959)

Objective: hypersonic flight/high altitude
Achieved: Mach 6.72 & altitude of 107,9 km

Aerodynamic heating:
Temperatures > 650°C

Titanium, Stainless steel
Ablative material
X-planes

X-29 (1984)

Testbed for
Effectiveness of forward swept wings
+ canards

Structural composites

Advanced avionics
X-planes

X-31 (1990)

Trust vectoring & maneuverability

Maintain controlled at high angles of attack

Break the “stall barrier”

Computer controlled canards
X-planes

STOVL in one airframe: Short (Vertical) Take Off & Landing
Competition between Boeing (X-32) & Lockheed Martin (X-35)
X-35 won and becomes JSF (Air Force, Navy & Marine Corps)
X-planes

X-45 (2002)
Unmanned Combat Air Vehicle (UCAV)

UAV with attack missions
Aerodynamics: from subsonic to hypersonic

Regimes of aerodynamic flow

<table>
<thead>
<tr>
<th>Regime</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>subsonic</td>
<td>$M &lt; 1$</td>
</tr>
<tr>
<td>sonic</td>
<td>$M = 1$ or</td>
</tr>
<tr>
<td>supersonic</td>
<td>$M &gt; 1$</td>
</tr>
<tr>
<td>transonic</td>
<td>$0.8 &lt; M &lt; 1.2$</td>
</tr>
<tr>
<td>supersonic</td>
<td>$1.2 &lt; M &lt; 5$</td>
</tr>
<tr>
<td>hypersonic</td>
<td>$M &gt; 5$</td>
</tr>
</tbody>
</table>

$M$ is the Mach number

$M$ is defined as: $M = \frac{V}{a}$

$a$ is the speed of sound (how large?)
Aerodynamics

**Subsonic**

Sound moves faster than object

\[ a > V \]

No coalescence of waves
(sound or pressure)

Doppler-effect *(what is this?)*
Aerodynamics

**Sonic**

Sound as fast as object

\[ a = V \]

Coalescence of waves
shock wave (pressure step)
“barrier”
Aerodynamics

**Supersonic**

Object moves faster than Sound

\[ V > a \]

Coalescence of waves

shock waves (pressure step)

\[ \mu \] (Mach angle)

\[ \mu = \sin \frac{a}{V} = \frac{1}{M} \]
What is the speed of this F-14?

\[\mu = 90^\circ - 30^\circ = 60^\circ\]

\[\sin \mu = \frac{1}{2} \sqrt{3} = 0.87\]

\[M = \frac{1}{\sin \mu} = 1.15\]

\[a = 340 \text{ m/s (S.L.)}\]

\[V = 391 \text{ m/s} = 1409 \text{ km/hr} = 761 \text{ kts}\]

Note: 
\[a = \sqrt{\gamma \cdot R \cdot T}\]

\[= \sqrt{1.4 \cdot 287 \cdot T}\]
Aerodynamics

Visualization of shock waves

http://www.youtube.com/watch?v=5UrW3swSMs4
Aerodynamics

Incompressible: until $M = 0.3$ (arbitrary – 5% decline)

Compressible: for $M > 0.3$

supersonic: complex

\[ V_1 < V_2 \]
\[ M_1 < M_2 \]
\[ p_2 > p_1 \]
\[ T_2 > T_1 \]
Aerodynamics

Shock waves induce:
- reduction of lift
- increase in drag (wave drag)
Aerodynamics

Reducing drag in supersonic flight

Option 1: Thin wing profiles: extending subsonic flow over profile increasing critical Mach number ($M_{cr}$)

$C_p$ (-) pressure coefficient at minimum pressure point of the airfoil

![Graph showing $C_p$ vs. Mach number ($M$) for thick and thin wings. The graph illustrates that for a thin wing, the pressure coefficient ($C_p$) is lower at a given Mach number ($M$), indicating reduced drag.](image)
Aerodynamics

Reducing drag in supersonic flight

Option 2: Swept wings
Aerodynamics

Effect of sweep angle $\Omega$ on L/D ratio for swept-wing AC
Aerodynamics

Transonic flight  High drag – “sound barrier”

Supersonic flight  Lower L/D ratio, but compensated by dynamic pressure $q$

$q = \frac{1}{2} \rho V^2$

Note: Starfighter F-104 ($M = 2+$); $S = 19.5 \, m^2$; $b = 6.9 \, m$; Aspect Ratio = 2.45; $t/c = 0.05$

What about take-off and landing speeds?
Aerodynamics

Hypersonic speeds – M > 5

Example X-15: “thermal barrier”

Very high skin (and stagnation) temperatures: T > 650°C

Special materials required:
Stainless steel, Titanium alloys; Special steel alloys like Inconel
Special Materials – high speed

<table>
<thead>
<tr>
<th></th>
<th>Alu 2024 T351</th>
<th>Ti-6Al-4V</th>
<th>Stainless 316</th>
<th>Inconel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. strength N/mm²</td>
<td>470</td>
<td>950</td>
<td>515</td>
<td>1110</td>
</tr>
<tr>
<td>Yield strength N/mm²</td>
<td>325</td>
<td>880</td>
<td>205</td>
<td>634</td>
</tr>
<tr>
<td>Max. elongation %</td>
<td>19</td>
<td>14</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Density kg/dm³</td>
<td>2.73</td>
<td>4.43</td>
<td>8</td>
<td>8.3</td>
</tr>
<tr>
<td>Modulus kN/mm²</td>
<td>70</td>
<td>114</td>
<td>193</td>
<td>210</td>
</tr>
</tbody>
</table>

Conventional: Aluminum
HT materials:
- Ti-6Al-4V (see graph)
- RVS 316
- Inconel

Maintain properties at higher temperatures!
Special Materials - Blackbird

First flight in 1964

Fastest (non-Exp.) aircraft (M3+)
Reconnaissance

Titanium (>90%)

Leading edge > 400° C

Cool down time half hour

Note Concorde <M2,02 (127° C)
because of Aluminum structure
Reentry from space

Mercury, Apollo programs

Capsules with ablative shields

Slowly sublimating surface

Dissipation of energy
Space Shuttle

TPS – Thermal Protection System
Up to 1650° C during reentry phase

- Reinforced Carbon-Carbon (RCC), nose cap, wing leading edges. Where temperature exceeds 1260 °C
- High-temperature reusable surface insulation (HRSI) tiles, used on the orbiter underside. Made of coated Silica ceramics. Used where temperature is below 1260 °C.
- Flexible Insulation Blankets (FIB), a quilted, flexible blanket-like surface insulation. Used where reentry temperature is below 649 °C (1200 °F).
Space Shuttle - TPS

Identification number
Each tile has an identification number which tells batch and location. This number can be fed into a computer to produce an identical tile.

Composition
90% air, 10% silica fibers a few millimeters thick. The tiles feels similar to plastic foam. The silica fibers are derived from high-quality sand.

Coating
The outer portion of a tile is covered with a black-glazed coating of borosilicate. These tiles do most of the coating job by shedding about 95% of the heat encountered. The remaining 5% is absorbed by the tile’s interior, preventing it from reaching the orbiter’s aluminum skin.

Glue
A silicon-rubber glue similar to common bathtub caulk, bonds a tile to a felt pad, that is in turn bonded to the orbiter’s skin. The felt absorbs the stresses of airframe bending that could damage the tiles.
Summary

Limits: speed – record is M = 6,72
altitude – record is 103 km

High temperatures – special materials
  – during supersonic/hypersonic flights
  - during reentry from space