Materials Design

From violins to superconducting magnets

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Department of Materials, University of Oxford
Overview

• What is Materials Science?

• Case studies
  – the violin
  – superconducting magnets

• Curriculum links

• Outreach activities
What is Materials Science?

Length scale

Crystal structure of YBCO

Nano-scale phase separation in NbTi

Micro-scale subgrain structure in YBCO

Large Hadron Collider magnets
Single-crystal titanium turbine blades in aircraft engines allow higher running temperatures giving greater economy.

Concrete reinforced with steel – self-healing concrete being developed to prevent damage by water penetration and corrosion.

Advances in LED technology leading to low-energy bulbs giving much improved light output.

Ceramic construction materials give added strength for less weight.

Cast iron engine block – replaced by lighter materials e.g. aluminium.

Lightweight alloys and composites – to improve fuel economy.

Smaller, faster silicon-based computer chips allowing improved safety and performance.

Highly reflective particles in paint improving visibility and safety.

Natural fibres with silver nanoparticles – to cut BO.

Complex miniaturised electronics revolutionising mobile communications.

Window panes with better insulating properties and a self-cleaning coating of nanoparticles.

Recyclable and biodegradable polymers to reduce pollution.

Stain-resistant nanomaterial coating – shrugs off dirt and liquid stains.

Shape memory metals that will return to their original shape after major distortion with the application of heat. Glasses do this at room temperature.

Powder-coated aluminium window frames – low maintenance and highly resistant to corrosion.
Case Study 1: the violin
The Violin

- Purpose of the box is to transmit vibrations of the strings into sound waves we can hear.
- Why is it this complex shape?
- Is wood the best material to use for the box?

“The violin explained”, J. Beament
Static Forces

String tension produces a downwards force of about **10Kg** onto the front of the violin.

... So we need the front plate to be **stiff** along the length of the violin so that it does not bend inwards under the weight of the strings.

Can achieve this by:

1) **Choice of material**
   - Using an intrinsically stiff material with **high Young’s Modulus** \( E = \frac{\text{stress } \sigma}{\text{strain } \varepsilon} \).

2) **Engineering design**
   - Using a **thicker cross section** of material – but this increases mass.
   - Shaping the front plate into an **arched shape** – same principle as a bridge.

“The violin explained”, J. Beament
How is violin sound produced?

When a string is plucked, standing waves are set up with frequencies determined by the string length and tension.

\[ f = \frac{1}{2L} \sqrt{\frac{T}{\mu}} \]

- **Fundamental frequency**
- **String tension**
- **String length**
- **Mass per unit length**

In fact, the actual wave in the string is a sum of the fundamental frequency with a series of higher harmonics.

... but the string itself makes very little sound!
How is violin sound produced?

String vibration from side to side makes bridge rock.

Sets up vibrations in the front plate of the violin body producing sound (pressure) waves.

To make a violin sound loud, we want to **maximise energy transfer** from strings to body.

Some resonant vibration modes of a model (symmetric) violin body.

Impedance matching

Every oscillator has an impedance – essentially how much force is required to make the system vibrate with a given amplitude.

To maximise energy transfer from one vibrating object to another need **impedance matching**.

The **speed of sound** in a material is very important for determining how sound will be transmitted through the body.

Speed of sound in a material:

\[
c = \sqrt{\frac{E}{\rho}}
\]

Young’s Modulus (stiffness)

Density

Sound radiation parameter:

\[
R = \frac{c}{\rho} = \frac{E^{1/2}}{\rho^{3/2}}
\]

→ maximise this quantity to maximise loudness

→ Make strings heavier

→ Make body lighter
Increasing sound “loudness”

Materials Selection

Lines of constant sound radiation ratio

\[ R = \frac{E^{1/2}}{\rho^{3/2}} \]

\[ \log R = \log E^{1/2} - \log \rho^{3/2} = \frac{1}{2} (\log E - 3 \log \rho) \]

\[ \log E = 3 \log \rho + 2 \log R \]

Materials Selection

Engineers – use these materials charts to choose best fit for a given application.

Materials scientists – interested in why different materials have different properties and how to design new materials with better properties.
Spruce microstructure

Scanning electron micrographs (taken 1993 with A. Heaver, Eng. Dept., Cambridge)

Mechanical properties governed by:
1) Cell wall mechanical properties
2) Microstructure – tubular arrangement of cells with air gaps → like foam structures.
Cell wall properties

Cell walls have **high Young's Modulus** because they consist of long cellulose fibres wound helically. The stiff cellulose fibres are embedded in softer hemi-cellulose and lignin, increasing toughness.

→ carbon fibre reinforced composites are based on the same principle.

<table>
<thead>
<tr>
<th>Material</th>
<th>monomer</th>
<th>Polymer length</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>Glucose (C₆H₁₂O₆)</td>
<td>7,000-15,000</td>
<td>Crystalline Strong</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Stiff</td>
</tr>
<tr>
<td>Hemi-cellulose</td>
<td>Glucose, xylose etc</td>
<td>500-3,000</td>
<td>Amorphous Weak</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Soft</td>
</tr>
</tbody>
</table>
Anisotropy

The Young’s Modulus of spruce is very different along the grain compared to across the grain → this directional behaviour is known as anisotropy.

Along the grain

Across the grain, structure can deform by bending cell walls rather than stretching the carbon backbone of the cellulose molecules.

Deformation along the grain is difficult because it involves stretching the strong covalent bonds in the cellulose molecules.


Ashby and Jones, Engineering Materials vol 2
1. CFRP has next highest **sound radiation coefficient** after wood (excluding foams as they are unsuitable for processing reasons).
Carbon-fibre reinforced composite

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2. To achieve the same anisotropy ratio as spruce in CFRP, we need to load the polymer with the right amount of carbon fibres (Volume fraction $V_f \sim 0.13$).
Carbon-fibre reinforced composite

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2. To achieve the same anisotropy ratio as spruce in CFRP, we need to load the polymer with the right amount of carbon fibres (Volume fraction \( V_f \sim 0.13 \)).

3. With \( V_f = 0.13 \), to match the resonant frequencies the mass of the front plate will be 2.7 times the mass of the spruce equivalent → too heavy.

Rule of mixtures for \( V_f=0.13 \)

\[
\begin{align*}
E_{CFRP} &= 53 \text{GPa} \\
\rho_{CFRP} &= 1.25 \text{Mg/m}^3 \\
f_{CFRP} &= A \left( \frac{E_{alomg}}{\rho} \right)^{1/2} t_{CFRP} \\
&= A \times 206 \times t_{CFRP} \\
&= A \times 0.52 = f_{spruce} \\
t_{CFRP} &= 2.5 \text{mm} \\
\text{mass}_{CFRP} &= 2.7 \times \text{mass}_{spruce}
\end{align*}
\]
Carbon-fibre reinforced composite

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To make a material with the required mechanical properties → need to sandwich a low density material (cardboard) between CFRP sheets.
Arching

Long fibres
- Good stiffness of the plate along length of violin to withstand string tension

Short fibres
- Greater flexibility to improve resonant properties
Cracks

The microstructure of wood such as spruce means that cracks can easily propagate along the grain.

Purfling

F-holes
Case study 2: superconducting magnets
Superconducting Magnets

• Electrical currents create magnetic fields

\[ B \propto I \]

magnetic field current

• A uniform field is produced inside a long coil of wire

Superconductors offer:
• Zero resistance
• Larger currents
• Higher magnetic fields
• Cheaper operation

• To generate large magnetic fields we need large currents

Conventional magnet
Superconducting magnet

www.magnet.fsu.edu
Only six different compounds are commercially available in wire form.
NbTi: the workhorse superconductor

- Nb is a ductile metal – easy to draw into wires.
- Reasonable critical temperature.
- Alloying with Ti enhances maximum magnetic field to over 10T.

3.5T MRI magnet

PROBLEM:-
Perfect NbTi  Low current
High Currents

- Magnetic field penetrates a superconductor in a lattice of “flux lines”.
- The core of the flux line becomes a normal conductor.
- Each flux line contains a specific amount of magnetic flux (a flux quantum).
- The spacing of flux lines decreases with applied magnetic field.

Electrical currents produce forces on flux lines.
- Movement of flux lines dissipates energy.
- To get large currents in high magnetic fields we need to “pin” the flux lines strongly.

Optimum pinning from “normal” defects about the same size and spacing as the flux lines.

\[ F \propto B \times I \]

[DOE report of the basic energy sciences workshop on superconductivity, 2006]
Thermo-mechanical process

- Multistage mechanical deformation followed by heat treatment to produce fine scale two-phase microstructure
- The deformation strain influences the final scale of the microstructure

Fabrication steps:
- Extrusion
- Rod Drawing
- Extrusion
- Rod and Wire Drawing

Microstructural Development:
- $\varepsilon_i = 0$
- $\varepsilon_i = 1.1$
- $\varepsilon_i = 2.5$
- $\varepsilon_i = 4.0$

Key:
- $\alpha$ - Ti
- $\beta$ - Nb - Ti

Lee and Larbalestier [Link](http://fs.magnet.fsu.edu/~lee/pubs/pub691s.pdf)
Optimised microstructure

- Thermo-mechanical process designed to optimise the material for a specific application (i.e. a particular magnetic field)

Typical spacing of flux lines

[Lee]
Wire processing

1. Cast high quality NbTi billet
2. Wrap in Nb foil to prevent Ti reacting with Cu sheath
3. Insert inside Cu stabiliser
4. Ram
5. Extrude to form wire
Multifilamentary Wire fabrication

Multi-stage process for fabricating LHC strand with:
• Diameter ~1mm
• Current >500 Amps (@2K, 10T)
Making Cables

- Multifilament strands are twisted together as ropes or braids or as “Rutherford cables”
- Twisting is crucial to control eddy currents and ac losses

Rutherford cable

LHC magnets:
- Each Rutherford cable (15x1.5mm) contains 36 strands
- Each strand contains 6300 filaments (0.006mm diameter)
- 7600 km of cable in total
- 250,000 km of strand

[Rogalla & Kes]
Beyond NbTi

Current Density Across Entire Cross-Section

- YBCO: Tape || Tape Plane
- YBCO: Tape _ Tape Plane
- Bi2223: B || Tape Plane
- Bi2223: B _ Tape Plane
- 2212: Round Wire 28% SC
- Nb₃Sn: Internal Sn RRP®
- Nb₃Sn: High Sn Bronze
- Nb-Ti: LHC 1.9 K
- MgB₂: 19Fil 24% Fill

Maximal Jₑ at 1.9 K for entire LHC NbTi strand production (CERN, Bourbou) '07. Reducing the temperature from 4.2 K produces a ~2 T shift in Jₑ for Nb-Ti.

[Courtesy of NHMFL, Florida]
Coated conductors

- <1% thickness of tape is superconductor
- Flexible metal substrate used to provide mechanical stability
- Grain alignment achieved in substrate or buffer layers
  - Act as template for HTS growth
- Buffers prevent chemical reactions with substrate
- Silver layer protects HTS from environmental damage

Courtesy of Superpower (http://www.superpower-inc.com)
Links to the National Curriculum

Chemistry
- Properties of Materials
- Bonding
- Extraction of metals
- Reactivity series
- Electrochemistry
- Polymers

Physics
- Forces
- Waves / light
- Energy
- Electricity
- Mechanics
- Superconductors
- Thermodynamics

Other Subjects: Maths, D&T, Biology
Course requirements - summary

<table>
<thead>
<tr>
<th>A-level requirements:</th>
<th>Three relevant A-Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Essential subjects</td>
<td>Recommended subjects</td>
</tr>
<tr>
<td>Materials Science</td>
<td>Maths and Physics</td>
</tr>
</tbody>
</table>

Typical offer:
- A-levels: A*AA
- IB: 40 including core points (with at least 7,6,6 at HL)
- or any other equivalent (see Admissions website)
Physics Aptitude Test

• This test is normally held on the first Wednesday in November and is ordinarily taken at your own school or college

• A single two hour test, covering both Physics and Mathematics.
  
  • Calculators will not be permitted for this two hour test

  • Concentrates on core knowledge common to all A-level syllabuses

  • Sample papers available from admissions office or Physics website:

  http://www.physics.ox.ac.uk/admissions/undergraduate/apptests.htm
# Success rates for Materials

<table>
<thead>
<tr>
<th></th>
<th>Applicants</th>
<th>Selected for Interview</th>
<th>Offered a Place</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Direct</td>
<td>PHYS2&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Direct</td>
</tr>
<tr>
<td>2014/2015</td>
<td>154</td>
<td>84</td>
<td>104</td>
</tr>
<tr>
<td>5 Yr Average</td>
<td>100</td>
<td>92</td>
<td>77</td>
</tr>
</tbody>
</table>

<sup>1</sup> Applicants to Physics who also indicate an interest in being considered for Materials (PHYS2)

<sup>2</sup>The number shows how many of these interviewees were PHYS2 applicants
How to find out more

• Ask questions today!
• jayne.shaw@materials.ox.ac.uk
• http://www.materials.ox.ac.uk

• University Undergraduate Prospectus
• Subject Undergraduate Prospectuses
• College Prospectuses
  www.ox.ac.uk/teacherseguide

• University website
  • www.oxford.ac.uk
  • www.admissions.ox.ac.uk

• Department Events
  • Masterclasses
  • Workshops
  • Residential Courses
  • Taster Days
  • Work Experience

• University Open Days - book a place for a college visit.
  Many colleges offer an overnight stay if you have to travel a long way.
  • www.admissions.ox.ac.uk/opendays/open2.shtml