CHAPTER 2

MATERIALS

Friday, February 03, 2017
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CHAPTER OUTLINE

- Material Strength and Stiffness
- Statistical Significance of Material Properties
- Strength and Cold Work
- Hardness
- Impact Properties
- Temperature Effects
- Numbering Systems
- Hot-Working Processes
- Cold-Working Processes
- Alloy Steels
- Corrosion-Resistant Steels
- Casting Materials
- Nonferrous Metals
- Plastics
- Composite Materials
- Materials Selection

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STANDARD TENSILE TEST

- Used to obtain material characteristics and strengths
- Loaded in tension with slowly increasing $P$
- Load and deflection are recorded

\[
\sigma = \frac{P}{A_0} \tag{2-1}
\]

\[
\epsilon = \frac{l - l_0}{l_0} \tag{2-2}
\]
STRESS-STRAIN DIAGRAM

- Linear relation until proportional limit, \( pl \)
- No permanent deformation until elastic limit, \( el \)
- Yield strength, \( S_y \)
- Ultimate strength, \( S_u \)
Elastica relationship of stress and strain

- \( E \) = modulus of elasticity
- Table A-5: typical values
- Usually independent of heat treatment, carbon content, or alloying

\[
\sigma = E\varepsilon
\]
TRUE STRESS-STRAIN DIAGRAM

- *Engineering* stress-strain diagram.
- *True* stress-strain diagram

\[ \varepsilon = \int_{l_0}^{l} \frac{dl}{l} = \ln \frac{l}{l_0} \]
COMPRESSION STRENGTH

- For ductile materials, $S_{uc} \approx S_{ut}$
- For brittle materials, $S_{uc} > S_{ut}$
TORSIONAL STRENGTHS

- Torsional strengths are found by twisting solid circular bars.
- Max shear stress is related to angle of twist by

\[ \tau_{\text{max}} = \frac{Gr}{l_0} \theta \]  

- \( \theta \) = angle of twist (radians)
- \( r \) = radius of bar
- \( l_0 \) = gauge length
- \( G \) = shear modulus or modulus of rigidity
TORSIONAL STRENGTHS

- Max shear stress is related to applied torque

\[ \tau_{\text{max}} = \frac{T r}{J} \]

\[ J = \frac{1}{2} \pi r^4 \]  

(2-6)

- *Torsional yield strength*, \( S_{sy} = \) max shear stress at the point where torque-twist diagram becomes significantly non-linear

- *Modulus of rupture*, \( S_{su} = \) max point on torque-twist diagram

\[ S_{su} = \frac{T u r}{J} \]  

(2-7)
RESILIENCE

- Resilience – Capacity of a material to absorb energy within its elastic range

- Modulus of resilience, $u_R$
  - Energy absorbed per unit volume without permanent deformation
  - Equals to area under stress-strain curve up to elastic limit
  - Elastic limit often approximated by yield point
RESILIENCE

- Area under curve to yield point gives approximation

\[ u_R \approx \int_{0}^{\epsilon_y} \sigma \, d\epsilon \]  

For two materials with the same yield strength, the less stiff material (lower \( E \)) has greater resilience.

\[ u_R \approx \frac{1}{2} S_y \epsilon_y = \frac{1}{2} (S_y)(S_y/E) = \frac{S_y^2}{2E} \]
TOUGHNESS

- **Toughness** – capacity of a material to absorb energy without fracture

- **Modulus of toughness,** $u_T$
  - Energy absorbed per unit volume without fracture
  - Equals area under stress-strain curve up to fracture point
TOUGHNESS

- Area under curve up to fracture point

\[ u_T = \int_0^{\varepsilon_f} \sigma \, d\varepsilon \]  \hspace{1cm} (2-10)

- Approximated by using average of yield & ultimate strengths and strain at fracture

\[ u_T \approx \left( \frac{S_y + S_{ut}}{2} \right) \varepsilon_f \]  \hspace{1cm} (2-11)

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STATISTICAL SIGNIFICANCE OF MATERIAL PROPERTIES

- Strength values are obtained from testing many nominally identical specimens.
- Strength, a material property, is distributional and thus statistical in nature.
EXAMPLE FOR STATISTICAL MATERIAL PROPERTY

- Histographic report for max stress of 1000 tensile tests on 1020 steel

<table>
<thead>
<tr>
<th>Class Midpoint $x_i$, kpsi</th>
<th>56.5</th>
<th>57.5</th>
<th>58.5</th>
<th>59.5</th>
<th>60.5</th>
<th>61.5</th>
<th>62.5</th>
<th>63.5</th>
<th>64.5</th>
<th>65.5</th>
<th>66.5</th>
<th>67.5</th>
<th>68.5</th>
<th>69.5</th>
<th>70.5</th>
<th>71.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class Frequency $f_i$</td>
<td>2</td>
<td>18</td>
<td>23</td>
<td>31</td>
<td>83</td>
<td>109</td>
<td>138</td>
<td>151</td>
<td>139</td>
<td>130</td>
<td>82</td>
<td>49</td>
<td>28</td>
<td>11</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

- Probability density: 
  # of occurrences divided by total sample number
EXAMPLE FOR STATISTICAL MATERIAL PROPERTY

Probability density function (See Ex. 20-4)

\[ f(x) = \frac{1}{2.594\sqrt{2\pi}} \exp \left[-\frac{1}{2} \left( \frac{x - 63.62}{2.594} \right)^2 \right] \]
STATISTICAL QUANTITY

- Statistical quantity described by mean, standard deviation, and distribution type

- From 1020 steel example:
  - Mean stress = 63.62 kpsi
  - Standard deviation = 2.594 kpsi
  - Distribution is normal

\[ S_{ut} = N(63.62, 2.594) \text{ kpsi} \]
STRENGTHS FROM TABLES

- Property tables often only report a single value for a strength term.
- Common to use 99% min strength, indicating 99% of samples exceed the reported value.
COLD WORK

- **Cold work**: Process of plastic straining below recrystallization temperature in the plastic region of stress-strain diagram

- Loading to point \(i\) beyond yield point, then unloading, causes permanent plastic deformation, \(\epsilon_p\)

- Reloading to point \(i\) behaves elastically all the way to \(i\), with additional elastic strain \(\epsilon_e\)

\[
\epsilon = \epsilon_p + \epsilon_e
\]

\[
\epsilon_e = \frac{\sigma_i}{E}
\]
COLD WORK

- Yield point is effectively increased to point i
- Material is less ductile (more brittle) since the plastic zone between yield strength & ultimate strength is reduced
- Repeated strain hardening can lead to brittle failure
HARDNESS

- **Hardness** – resistance of a material to penetration by a pointed tool

- Most common hardness-measuring systems
  - Rockwell
  - Brinell
  - Vickers
STRENGTH AND HARDNESS

For steels

\[ S_u = \begin{cases} 
0.5H_B & \text{kpsi} \\
3.4H_B & \text{MPa} 
\end{cases} \quad (2-21) \]

For cast iron

\[ S_u = \begin{cases} 
0.23H_B - 12.5 \text{ kpsi} \\
1.58H_B - 86 \text{ MPa} 
\end{cases} \quad (2-22) \]
IMPACT PROPERTIES

- Charpy notched-bar test used to determine brittleness and impact strength
- Specimen struck by pendulum
- Energy absorbed: computed from height of swing after fracture
EFFECT OF TEMPERATURE ON IMPACT

Charpy, ft·lbf

Temperature, °F

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TEMPERATURE EFFECTS ON STRENGTHS

- Strength vs. temperature for carbon & alloy steels
- As temperature increases above RT:
  - $S_{ut}$ increases slightly, then decreases significantly
  - $S_y$ decreases continuously

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**CREEP**

- **Creep**: continuous deformation under load for long periods of time at elevated temperatures
Common numbering systems

- Society of Automotive Engineers (SAE)
- American Iron and Steel Institute (AISI)
- Unified Numbering System (UNS)
- American Society for Testing and Materials (ASTM) for cast irons
UNS NUMBERING SYSTEM

- Established by SAE in 1975
- Letter prefix followed by 5 digit number
- Letter prefix designates material class
  - G – carbon and alloy steel
  - A – Aluminum alloy
  - C – Copper-based alloy
  - S – Stainless or corrosion-resistant steel
UNS FOR STEELS, G

- First two numbers indicate composition, excluding carbon content

<table>
<thead>
<tr>
<th>G10</th>
<th>Plain carbon</th>
<th>G46</th>
<th>Nickel-molybdenum</th>
</tr>
</thead>
<tbody>
<tr>
<td>G11</td>
<td>Free-cutting carbon steel with more sulfur or phosphorus</td>
<td>G48</td>
<td>Nickel-molybdenum</td>
</tr>
<tr>
<td>G13</td>
<td>Manganese</td>
<td>G50</td>
<td>Chromium</td>
</tr>
<tr>
<td>G23</td>
<td>Nickel</td>
<td>G51</td>
<td>Chromium</td>
</tr>
<tr>
<td>G25</td>
<td>Nickel</td>
<td>G52</td>
<td>Chromium</td>
</tr>
<tr>
<td>G31</td>
<td>Nickel-chromium</td>
<td>G61</td>
<td>Chromium-vanadium</td>
</tr>
<tr>
<td>G33</td>
<td>Nickel-chromium</td>
<td>G86</td>
<td>Chromium-nickel-molybdenum</td>
</tr>
<tr>
<td>G40</td>
<td>Molybdenum</td>
<td>G87</td>
<td>Chromium-nickel-molybdenum</td>
</tr>
<tr>
<td>G41</td>
<td>Chromium-molybdenum</td>
<td>G92</td>
<td>Manganese-silicon</td>
</tr>
<tr>
<td>G43</td>
<td>Nickel-chromium-molybdenum</td>
<td>G94</td>
<td>Nickel-chromium-molybdenum</td>
</tr>
</tbody>
</table>

- Second pair of numbers indicates carbon content in hundredths of a percent by weight
- Fifth number is used for special situations
- Example: G52986 is chromium alloy with 0.98% carbon

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ALLOY STEELS

- Chromium
- Nickel
- Manganese
- Silicon
- Molybdenum
- Vanadium
- Tungsten
CORROSION-RESISTANT STEELS

Stainless steels

• Iron-base alloys with at least 12 % chromium
• Resists many corrosive conditions

Four types of stainless steels

• Ferritic chromium
• Austenitic chromium-nickel
• Martensitic
• Precipitation-hardenable
CASTING MATERIALS

- Gray Cast Iron
- Ductile and Nodular Cast Iron
- White Cast Iron
- Malleable Cast Iron
- Alloy Cast Iron
- Cast Steel
NONFERROUS METALS

- Aluminum
- Magnesium
- Titanium
NONFERROUS METALS

Copper-based alloys

- **Brass with 5 to 15 % zinc**
  - Gilding brass, commercial bronze, red brass
- **Brass with 20 to 36 % zinc**
  - Low brass, cartridge brass, yellow brass
  - Low-leaded brass, high-leaded brass (engraver’s brass), free-cutting brass
  - Admiralty metal
  - Aluminum brass
- **Brass with 36 to 40 % zinc**
  - Muntz metal, naval brass
- **Bronze**
  - Silicon bronze, phosphor bronze, aluminum bronze, beryllium bronze
PLASTICS

- **Thermoplastic** – any plastic that flows or is moldable when heat is applied

- **Thermoset** – a plastic for which the polymerization process is finished in a hot molding press where the plastic is liquefied under pressure
**TABLE 2-2: THERMOPLASTIC PROPERTIES**

<table>
<thead>
<tr>
<th>Name</th>
<th>$S_u$ kpsi</th>
<th>$E$ Mpsi</th>
<th>Hardness Rockwell</th>
<th>Elongation %</th>
<th>Dimensional Stability</th>
<th>Heat Resistance</th>
<th>Chemical Resistance</th>
<th>Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS group</td>
<td>2–8</td>
<td>0.10–0.37</td>
<td>60–110R</td>
<td>3–50</td>
<td>Good</td>
<td>*</td>
<td>Fair</td>
<td>EMST</td>
</tr>
<tr>
<td>Acetal group</td>
<td>8–10</td>
<td>0.41–0.52</td>
<td>80–94M</td>
<td>40–60</td>
<td>Excellent</td>
<td>Good</td>
<td>High</td>
<td>M</td>
</tr>
<tr>
<td>Acrylic</td>
<td>5–10</td>
<td>0.20–0.47</td>
<td>92–110M</td>
<td>3–75</td>
<td>High</td>
<td>*</td>
<td>Fair</td>
<td>EMS</td>
</tr>
<tr>
<td>Fluoroplastic group</td>
<td>0.50–7</td>
<td>...</td>
<td>50–80D</td>
<td>100–300</td>
<td>High</td>
<td>Excellent</td>
<td>Excellent</td>
<td>MPR †</td>
</tr>
<tr>
<td>Nylon</td>
<td>8–14</td>
<td>0.18–0.45</td>
<td>112–120R</td>
<td>10–200</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
<td>CEM</td>
</tr>
<tr>
<td>Phenylene oxide</td>
<td>7–18</td>
<td>0.35–0.92</td>
<td>115R, 106L</td>
<td>5–60</td>
<td>Excellent</td>
<td>Good</td>
<td>Fair</td>
<td>EFM</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>8–16</td>
<td>0.34–0.86</td>
<td>62–91M</td>
<td>10–125</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Fair</td>
<td>EMS</td>
</tr>
<tr>
<td>Polyester</td>
<td>8–18</td>
<td>0.28–1.6</td>
<td>65–90M</td>
<td>1–300</td>
<td>Excellent</td>
<td>Poor</td>
<td>Excellent</td>
<td>CLMR</td>
</tr>
<tr>
<td>Polyimide</td>
<td>6–50</td>
<td>...</td>
<td>88–120M</td>
<td>Very low</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent †</td>
<td>CLMP</td>
</tr>
<tr>
<td>Polyphenylene sulfide</td>
<td>14–19</td>
<td>0.11</td>
<td>122R</td>
<td>1.0</td>
<td>Good</td>
<td>Excellent</td>
<td>Excellent</td>
<td>M</td>
</tr>
<tr>
<td>Polystyrene group</td>
<td>1.5–12</td>
<td>0.14–0.60</td>
<td>10–90M</td>
<td>0.5–60</td>
<td>...</td>
<td>Poor</td>
<td>Poor</td>
<td>EM</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>10</td>
<td>0.36</td>
<td>120R</td>
<td>50–100</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent †</td>
<td>EFM</td>
</tr>
<tr>
<td>Polyvinyl chloride</td>
<td>1.5–7.5</td>
<td>0.35–0.60</td>
<td>65–85D</td>
<td>40–450</td>
<td>...</td>
<td>Poor</td>
<td>Poor</td>
<td>EFM</td>
</tr>
</tbody>
</table>

*Heat-resistant grades available.
†With exceptions.

C Coatings  L Laminates  R Resins  E Extrusions  M Moldings  S Sheet  F Foams  P Press and sinter methods  T Tubing
# TABLE 2-3: THERMOSET PROPERTIES

<table>
<thead>
<tr>
<th>Name</th>
<th>$S_u$ kpsi</th>
<th>$E$ Mpsi</th>
<th>Hardness Rockwell</th>
<th>Elongation %</th>
<th>Dimensional Stability</th>
<th>Heat Resistance</th>
<th>Chemical Resistance</th>
<th>Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkyd</td>
<td>3–9</td>
<td>0.05–0.30</td>
<td>99M*</td>
<td>...</td>
<td>Excellent</td>
<td>Good</td>
<td>Fair</td>
<td>M</td>
</tr>
<tr>
<td>Allylic</td>
<td>4–10</td>
<td>...</td>
<td>105–120M</td>
<td>...</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>CM</td>
</tr>
<tr>
<td>Amino group</td>
<td>5–8</td>
<td>0.13–0.24</td>
<td>110–120M</td>
<td>0.30–0.90</td>
<td>Good</td>
<td>Excellent*</td>
<td>Excellent*</td>
<td>LR</td>
</tr>
<tr>
<td>Epoxy</td>
<td>5–20</td>
<td>0.03–0.30*</td>
<td>80–120M</td>
<td>1–10</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>CMR</td>
</tr>
<tr>
<td>Phenolics</td>
<td>5–9</td>
<td>0.10–0.25</td>
<td>70–95E</td>
<td>...</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Good</td>
<td>EMR</td>
</tr>
<tr>
<td>Silicons</td>
<td>5–6</td>
<td>...</td>
<td>80–90M</td>
<td>...</td>
<td>Excellent</td>
<td>Excellent</td>
<td>CLMR</td>
<td></td>
</tr>
</tbody>
</table>

*With exceptions.

C Coatings  L Laminates  R Resins  E Extrusions  M Moldings  S Sheet  F Foams  P Press and sinter methods  T Tubing
COMPOSITE MATERIALS

- Formed from two or more dissimilar materials, each of which contributes to the final properties.
- Materials remain distinct from each other at the macroscopic level.
- Often consists of *laminates* of *filler* to provide stiffness and strength and a *matrix* to hold the material together.
Common filler types:

- Particulate composite
- Randomly oriented short fiber composite
- Unidirectional continuous fiber composite
- Woven fabric composite
<table>
<thead>
<tr>
<th>Family</th>
<th>Classes</th>
<th>Short Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals (the metals and alloys of engineering)</td>
<td>Aluminum alloys</td>
<td>Al alloys</td>
</tr>
<tr>
<td></td>
<td>Copper alloys</td>
<td>Cu alloys</td>
</tr>
<tr>
<td></td>
<td>Lead alloys</td>
<td>Lead alloys</td>
</tr>
<tr>
<td></td>
<td>Magnesium alloys</td>
<td>Mg alloys</td>
</tr>
<tr>
<td></td>
<td>Nickel alloys</td>
<td>Ni alloys</td>
</tr>
<tr>
<td></td>
<td>Carbon steels</td>
<td>Steels</td>
</tr>
<tr>
<td></td>
<td>Stainless steels</td>
<td>Stainless steels</td>
</tr>
<tr>
<td></td>
<td>Tin alloys</td>
<td>Tin alloys</td>
</tr>
<tr>
<td></td>
<td>Titanium alloys</td>
<td>Ti alloys</td>
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<tr>
<td></td>
<td>Tungsten alloys</td>
<td>W alloys</td>
</tr>
<tr>
<td></td>
<td>Lead alloys</td>
<td>Pb alloys</td>
</tr>
<tr>
<td></td>
<td>Zinc alloys</td>
<td>Zn alloys</td>
</tr>
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</table>
# TABLE 2-4: MATERIAL FAMILIES AND CLASSES

<table>
<thead>
<tr>
<th>Family</th>
<th>Classes</th>
<th>Short Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramics</td>
<td>Alumina</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td>Technical ceramics</td>
<td>Aluminum nitride</td>
<td>AlN</td>
</tr>
<tr>
<td>(fine ceramics)</td>
<td>Boron carbide</td>
<td>B₄C</td>
</tr>
<tr>
<td>capable of</td>
<td>Silicon carbide</td>
<td>SiC</td>
</tr>
<tr>
<td>load-bearing application</td>
<td>Silicon nitride</td>
<td>Si₃N₄</td>
</tr>
<tr>
<td></td>
<td>Tungsten carbide</td>
<td>WC</td>
</tr>
<tr>
<td>Nontechnical ceramics</td>
<td>Brick</td>
<td>Brick</td>
</tr>
<tr>
<td>(porous ceramics of</td>
<td>Concrete</td>
<td>Concrete</td>
</tr>
<tr>
<td>construction)</td>
<td>Stone</td>
<td>Stone</td>
</tr>
<tr>
<td>Glasses</td>
<td>Soda-lime glass</td>
<td>Soda-lime glass</td>
</tr>
<tr>
<td></td>
<td>Borosilicate glass</td>
<td>Borosilicate glass</td>
</tr>
<tr>
<td></td>
<td>Silica glass</td>
<td>Silica glass</td>
</tr>
<tr>
<td></td>
<td>Glass ceramic</td>
<td>Glass ceramic</td>
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<tr>
<td>Family</td>
<td>Classes</td>
<td>Short Name</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>Polymers (the thermoplastics and thermosets of engineering)</td>
<td>Acrylonitrile butadiene styrene</td>
<td>ABS</td>
</tr>
<tr>
<td></td>
<td>Cellulose polymers</td>
<td>CA</td>
</tr>
<tr>
<td></td>
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<td>Epoxies</td>
<td>Epoxy</td>
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<tr>
<td></td>
<td>Phenolics</td>
<td>Phenolics</td>
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<tr>
<td></td>
<td>Polyamides (nylons)</td>
<td>PA</td>
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<td></td>
<td>Polycarbonate</td>
<td>PC</td>
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<td>Polyesters</td>
<td>Polyester</td>
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<td></td>
<td>Polyetheretherketone</td>
<td>PEEK</td>
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<td></td>
<td>Polyethylene</td>
<td>PE</td>
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<tr>
<td></td>
<td>Polyethylene terephalate</td>
<td>PET or PETE</td>
</tr>
<tr>
<td></td>
<td>Polymethylmethacrylate</td>
<td>PMMA</td>
</tr>
<tr>
<td></td>
<td>Polyoxymethylene(Acetal)</td>
<td>POM</td>
</tr>
<tr>
<td></td>
<td>Polypropylene</td>
<td>PP</td>
</tr>
<tr>
<td></td>
<td>Polystyrene</td>
<td>PS</td>
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<tr>
<td></td>
<td>Polytetrafluorethylene</td>
<td>PTFE</td>
</tr>
<tr>
<td></td>
<td>Polyvinylchloride</td>
<td>PVC</td>
</tr>
<tr>
<td>Family</td>
<td>Classes</td>
<td>Short Name</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Elastomers (engineering rubbers, natural and synthetic)</td>
<td>Butyl rubber, EVA, Isoprene, Natural rubber, Polychloroprene (Neoprene), Polyurethane, Silicon elastomers</td>
<td>Butyl rubber, EVA, Isoprene, Natural rubber, Neoprene, PU, Silicons</td>
</tr>
<tr>
<td>Hybrids</td>
<td>Carbon-fiber reinforced polymers, Glass-fiber reinforced polymers, SiC reinforced aluminum, Flexible polymer foams, Rigid polymer foams</td>
<td>CFRP, GFRP, Al-SiC, Flexible foams, Rigid foams</td>
</tr>
<tr>
<td>Composites</td>
<td>Cork, Bamboo, Wood</td>
<td>Cork, Bamboo, Wood</td>
</tr>
<tr>
<td>Foams</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural materials</td>
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YOUNG’S MODULUS FOR VARIOUS MATERIALS