Engineering Thermoplastics
Nylons (PA), Acetals (POM), Polyesters (PBT and PET),
PC, Acrylics (PMMA), PTFE, PPO, PPS, PEEK

Professor Joe Greene
CSU, CHICO
Polyamide History

• PA is considered the first engineering thermoplastic
• PA is one of many heterochain thermoplastics, which has atoms other than C in the chain.
• PA invented in 1928 by Wallace Carothers, DuPont, in search of a “super polyester” fiber with molecular weights greater than 10,000. First commercial nylon in 1938.
• PA was created when a condensation reaction occurred between amino acids, dibasic acids, and diamines.
• Nylons are described by a numbering system which indicates the number of carbon atoms in the monomer chains
  – Amino acid polymers are designated by a single number, as nylon 6
  – Diamines and dibasic acids are designated with 2 numbers, the first representing the diamine and the second indicating the adipic acid, as in nylon 6,6 or nylon 6,10 with sebacic acid.
Chemistry & Chemical Structure
linear polyamides

• Thermoplastic nylons have amide (CONH) repeating link

• Nylon 6,6 - poly-hexamethylene-diamine (linear)
  \[ \text{hexamethylene diamine} + \text{Adipic Acid} \]
  \[ n[\text{NH}_2(\text{CH}_2)_6\text{NH} \cdot \text{CO} (\text{CH}_2)_4\text{COOH} ] + (\text{heat}) \]
  nylon salt
  \[ [\text{NH}_2(\text{CH}_2)_6\text{NH} \cdot \text{CO} (\text{CH}_2)_4\text{CO} ]_n + \text{nH}_2\text{O} \]
  Nylon 6,6 polymer chain

• Nylon 6 - polycapro lactam (linear)
  \[ [\text{NH}(\text{CH}_2)_5\text{CO} ]_n \]
Chemistry & Chemical Structure
linear polyamides

• Nylon 6, 10 - polyhexamethylenesebacamide (linear)
  \([\text{NH}_2(\text{CH}_2)_6\text{NH} \cdot \text{CO} (\text{CH}_2)_8\text{CO}]_n\)

• Nylon 11 - Poly(11-amino-undecanoic-amide (linear)
  \([\text{NH}(\text{CH}_2)_{10}\text{CO}]_n\)

• Nylon 12 - Poly(11-amino-undecanoic-amide (linear)
  \([\text{NH}(\text{CH}_2)_{11}\text{CO}]_n\)

• Other Nylons
  – Nylon 8, 9, 46, and copolymers from other diamines and acids
Chemistry & Chemical Structure
Aromatic polyamides (aramids)

- **PMPI** - poly m-phenylene isophthalamide (LCP fiber)
  \[ \text{[} -\text{NHCO} - \text{NHCO} \text{]_n} \]

- **PPPT** - poly p-phenylene terephthalamide (LCP fiber)
  \[ \text{[} -\text{NHCO} - \text{NHCO} \text{]_n} \]

- Nomax PMPI - first commercial aramid fiber for electrical insulation. LCP fibers feature straight chain crystals
- Kevlar 29 PPPT - textile fiber for tire cord, ropes, cables etc.
- Kevlar 49 PPPT - reinforcing fiber for thermosetting resins
Chemistry & Chemical Structure

Transparent polyamides

• PA- (6,3,T)
  \[\text{[CH}_2\text{C}_3\text{H}_6\text{C}_2\text{H}_4\text{-NHCO} - \bigcirc \text{NHCO } ]_n\]

• PA - (6,T)
  \[\text{[(CH}_2\text{)}_6\text{NHCO} - \bigcirc \text{NHCO } ]_n\]

• Transparent polyamides are commercially available
• Reduced crystallization due to introduction of side groups
Applications for Polyamides

• Fiber applications
  – 50% into tire cords (nylon 6 and nylon 6,6)
  – rope, thread, cord, belts, and filter cloths.
  – Monofilaments- brushes, sports equipment, and bristles (nylon 6,10)

• Plastics applications
  – bearings, gears, cams
  – rollers, slides, door latches, thread guides
  – clothing, light tents, shower curtains, umbrellas
  – electrical wire jackets (nylon 11)

• Adhesive applications
  – hot melt or solution type
  – thermoset reacting with epoxy or phenolic resins
  – flexible adhesives for bread wrappers, dried soup packets, bookbindings
# Mechanical Properties of Polyamides

## Mechanical Properties of Nylon

<table>
<thead>
<tr>
<th></th>
<th>Nylon 6</th>
<th>Nylon 6,6</th>
<th>Nylon 6,10</th>
<th>Nylon 6,12</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density, g/cc</strong></td>
<td>1.13-1.15</td>
<td>1.13-1.15</td>
<td>1.09</td>
<td>1.06-1.10</td>
</tr>
<tr>
<td><strong>Crystallinity</strong></td>
<td>30-% - 50%</td>
<td>30-% - 50%</td>
<td>30-% - 50%</td>
<td>30-% - 50%</td>
</tr>
<tr>
<td><strong>Molecular Weight</strong></td>
<td>10,000–30,000</td>
<td>10,000–30,000</td>
<td>10,000–30,000</td>
<td>10,000–30,000</td>
</tr>
<tr>
<td><strong>Tensile Strength, psi</strong></td>
<td>6,000 – 24,000</td>
<td>14,000</td>
<td>8,500 – 8,600</td>
<td>6,500 – 8,800</td>
</tr>
<tr>
<td><strong>Tensile Modulus, psi</strong></td>
<td>300K</td>
<td>230K – 550K</td>
<td>250 K</td>
<td>220 - 290 K</td>
</tr>
<tr>
<td><strong>Tensile Elongation, %</strong></td>
<td>30% - 100%</td>
<td>15%-80%</td>
<td>70%</td>
<td>150%</td>
</tr>
<tr>
<td><strong>Impact Strength ft-lb/in</strong></td>
<td>0.6 – 2.2</td>
<td>0.55 – 1.0</td>
<td>1.2</td>
<td>1.0 – 1.9</td>
</tr>
<tr>
<td><strong>Hardness</strong></td>
<td>R80 - 102</td>
<td>R120</td>
<td>R111</td>
<td>M78</td>
</tr>
</tbody>
</table>
# Physical Properties of Polyamide

<table>
<thead>
<tr>
<th></th>
<th>Nylon 6</th>
<th>Nylon 6,6</th>
<th>Nylon 6,10</th>
<th>Nylon 6,12</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optical</strong></td>
<td>Translucent to opaque</td>
<td>Translucent to opaque</td>
<td>Translucent to opaque</td>
<td>Translucent to opaque</td>
</tr>
<tr>
<td><strong>Tmelt</strong></td>
<td>210°C - 220°C</td>
<td>255°C – 265°C</td>
<td>220°C</td>
<td>195°C – 219°C</td>
</tr>
<tr>
<td><strong>Tg</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>H₂O Absorption</strong></td>
<td>1.3-1.9% (24h)</td>
<td>1.0-2.8% (24h)</td>
<td>1.4% (24h)</td>
<td>0.4 – 1.0% (24h)</td>
</tr>
<tr>
<td></td>
<td>8.5-10 (Max)</td>
<td>8.5% (Max)</td>
<td>3.3% (Max)</td>
<td>2.5 – 3% (Max)</td>
</tr>
<tr>
<td><strong>Oxidation Resistance</strong></td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td><strong>UV Resistance</strong></td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td><strong>Solvent Resistance</strong></td>
<td>Dissolved by phenol &amp; formic acid</td>
<td>Dissolved by phenol &amp; formic acid</td>
<td>Dissolved by phenol &amp; formic acid</td>
<td>Dissolved by phenol &amp; formic acid</td>
</tr>
<tr>
<td><strong>Alkaline Resistance</strong></td>
<td>Resistant</td>
<td>Resistant</td>
<td>Resistant</td>
<td>Resistant</td>
</tr>
<tr>
<td><strong>Acid Resistance</strong></td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td><strong>Cost $/lb</strong></td>
<td>$1.30</td>
<td>$1.30</td>
<td>$3.00</td>
<td>$3.10</td>
</tr>
</tbody>
</table>
Advantages Disadvantages of Polyamide

• **Advantages**
  - Tough, strong, impact resistant
  - Low coefficient of friction
  - Abrasion resistance
  - High temperature resistance
  - Processable by thermoplastic methods
  - Good solvent resistance
  - Resistant to bases

• **Disadvantages**
  - High moisture absorption with dimensional instability
    • loss of up to 30% of tensile strength and 50% of tensile modulus
  - Subject to attack by strong acids and oxidizing agents
  - Requires UV stabilization
  - High shrinkage in molded sections
  - Electrical and mechanical properties influenced by moisture content
  - Dissolved by phenols
Additives and Reinforcements to PA

- Additives- antioxidants, UV stabilizers, colorants, lubricants
- Fillers
  - Talc
  - Calcium carbonate
- Reinforcements
  - Glass fiber- short fiber (1/8” or long fiber 1/4”)
  - Mineral fiber (wolastonite)
  - carbon fibers
  - graphite fibers
  - metallic flakes
  - steel fibers
# Properties of Reinforced Nylon

<table>
<thead>
<tr>
<th></th>
<th>Nylon 6,6</th>
<th>Nylon 6,6 with 30% short glass</th>
<th>Nylon 6,6 with 30% long glass</th>
<th>Nylon 6,6 with 30% carbon fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density, g/cc</strong></td>
<td>1.13-1.15</td>
<td>1.4</td>
<td>1.4</td>
<td>1.06-1.10</td>
</tr>
<tr>
<td><strong>Crystallinity</strong></td>
<td>30-% - 50%</td>
<td>30-% - 50%</td>
<td>30-% - 50%</td>
<td>30-% - 50%</td>
</tr>
<tr>
<td><strong>Molecular Weight</strong></td>
<td>10,000–30,000</td>
<td>30,000</td>
<td>10,000–30,000</td>
<td>10,000–30,000</td>
</tr>
<tr>
<td><strong>Tensile Strength, psi</strong></td>
<td>14,000</td>
<td>28,000</td>
<td>28,000</td>
<td>32,000</td>
</tr>
<tr>
<td><strong>Tensile Modulus, psi</strong></td>
<td>230K – 550K</td>
<td>1,300K</td>
<td>1,400 K</td>
<td>3,300 K</td>
</tr>
<tr>
<td><strong>Tensile Elongation, %</strong></td>
<td>15%-80%</td>
<td>3%</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td><strong>Impact Strength ft-lb/in</strong></td>
<td>0.55 – 1.0</td>
<td>1.6-4.5</td>
<td>4.0</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Hardness</strong></td>
<td>R120</td>
<td>R120</td>
<td>E60</td>
<td>R120</td>
</tr>
<tr>
<td><strong>Moisture %</strong></td>
<td>1.0-2.8% (24h) 8.5% (Max)</td>
<td>0.7-1.1 (24h) 5.5-6.5 (Max)</td>
<td>0.9 (24h) 5.5-6.5 (Max)</td>
<td>0.7 (24h) 5 (Max)</td>
</tr>
<tr>
<td><strong>Cost $/lb</strong></td>
<td>$1.40</td>
<td>$1.70</td>
<td>$2.00</td>
<td>$2.70</td>
</tr>
</tbody>
</table>
Other Heterochain Polymers

• Polyimide
  – Developed by Du Pont in 1962
  – Obtained from a condensation polymerization of aromatic diamine and an aromatic dianhydride
  – Characterized as Linear thermoplastics that are difficult to process
  – Many polyimides do not melt but are fabricated by machining
  – Molding can occur if enough time for flow is allowed for $T>T_g$

• Advantages
  – High temperature service (up to 700°C)
  – Excellent barrier, electrical properties, solvent and wear resistance
  – Good adhesion and especially suited for composite fabrication
Other Heterochain Polymers

• Polyimide Disadvantages
  – Difficulty to fabricate and requires venting of volatiles
  – Hydroscopic
  – Subject to attacks by alkalines
  – Comparatively high cost

• Applications
  – Aerospace, electronics, and nuclear uses (competes with fluoro carbons)
  – Office and industrial equipment; Laminates, dielectrics, and coatings
  – Valve seats, gaskets, piston rings, thrust washers, and bushings

• Polyamide-imide
  – Amorphous member of imide family, marketed in 1972 (Torlon), and used in aerospace applications such as jet engine components
  – Contains aromatic rings and nitrogen linkage
  – Advantages include: High temperature properties (500F), low coefficient of friction, and dimensional stability.
Other Heterochain Polymers

- **Polyacetal or Polyoxymethylene (POM)**
  - Polymerized from formaldehyde gas
  - First commercialized in 1960 by Du Pont
  - Similar in properties to Nylon and used for plumbing fixtures, pump impellers, conveyor belts, aerosol stem valves, VCR tape housings

- **Advantages**
  - Easy to fabricate, has glossy molded surfaces, provide superior fatigue endurance, creep resistance, stiffness, and water resistance.
  - Among the strongest and stiffest thermoplastics.
  - Resistant to most chemicals, stains, and organic solvents

- **Disadvantages**
  - Poor resistance to acids and bases and difficult to bond
  - Subject to UV degradation and is flammable
  - Toxic fumes released upon degradation
# Mechanical Properties

<table>
<thead>
<tr>
<th></th>
<th>Nylon 6</th>
<th>Acetal</th>
<th>Polyimid</th>
<th>Polyamide-imide</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density, g/cc</strong></td>
<td>1.13-1.15</td>
<td>1.42</td>
<td>1.43</td>
<td>1.41</td>
</tr>
<tr>
<td><strong>Crystallinity</strong></td>
<td>30-% - 50%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Molecular Weight</strong></td>
<td>10,000–30,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tensile Strength, psi</strong></td>
<td>6,000 – 24,000</td>
<td>10,000</td>
<td>10,000</td>
<td>26,830</td>
</tr>
<tr>
<td><strong>Tensile Modulus, psi</strong></td>
<td>300K</td>
<td>520K</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tensile Elongation, %</strong></td>
<td>30% - 100%</td>
<td>40% - 75%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Impact Strength ft-lb/in</strong></td>
<td>0.6 – 2.2</td>
<td>0.07</td>
<td>0.9</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Hardness</strong></td>
<td>R80 - 102</td>
<td>R120</td>
<td>E50</td>
<td>E78</td>
</tr>
<tr>
<td><strong>Tmelt</strong></td>
<td>210 - 220 C</td>
<td>175-181 C</td>
<td></td>
<td>Tg=275C</td>
</tr>
<tr>
<td><strong>Moisture 24 hr max</strong></td>
<td>1.3 - 1.9%</td>
<td>0.25 to 0.40%</td>
<td>0.32%</td>
<td>.28%</td>
</tr>
<tr>
<td><strong>Optical</strong></td>
<td>Translucent to opaque</td>
<td>Translucent to opaque</td>
<td>opaque</td>
<td>Transparent to opaque</td>
</tr>
</tbody>
</table>
Polyester History

• 1929 W. H. Carothers suggested classification of polymers into two groups, *condensation* and *addition* polymers.

• Carothers was not successful in developing polyester fibers from linear aliphatic polyesters due to low melting point and high solubility. No commercial polymer is based on these.

• p-phenylene group is added for stiffening and leads to polymers with high melting points and good fiber-forming properties, e.g., PET.

• Polymers used for films and for fibers

• Polyesters is one of many heterochain thermoplastics, which has atoms other than C in the chain.

• Polyesters includes unsaturated *(thermosets)*, saturated and aromatic *thermoplastic* polyesters.
Chemistry & Chemical Structure

linear polyesters (versus branched)

- Thermoplastic polyesters have ester(-C-O) repeating link
- Polyester (linear) PET and PBT

\[
\text{C}_6\text{H}_4(\text{COOH})_2 + (\text{CH}_2)_2(\text{OH})_2 \rightarrow \text{-[\{(CH}_2\}_2 -O- \text{C} \quad \text{O} \quad \text{O} \quad \text{C-O}\]-} \\
\text{terephthalic acid} \quad + \text{ethylene glycol} \quad \text{Polyethylene terephthalate (PET)}
\]

\[
\text{C}_6\text{H}_4(\text{COOH})_2 + (\text{CH}_2)_4(\text{OH})_2 \rightarrow \text{-[\{(CH}_2\}_4 -O- \text{C} \quad \text{O} \quad \text{O} \quad \text{C-O}\]-} \\
\text{terephthalic acid} \quad + \text{butylene glycol} \quad \text{Polybutylene terephthalate (PBT)}
\]
Chemistry & Chemical Structure
linear polyesters (versus branched)

• Wholly aromatic copolyesters (LCP)
  – High melting sintered: Oxybenzoyl (does not melt below its decomposition temperature. Must be compression molded)
  – Injection moldable grades: Xydar and Vectra

  – Xydar (Amoco Performance Products)
    • terephthalic acid, p,p’- dihydroxybiphenyl, and p-hydroxybenzoic acid
      – Grade 1: HDT of 610F
      – Grade 2: HDT of 480 F
  – Vectra (Hoechst Celanese Corp.)
    • para-hydroxybenzoic acid and hydroxynaphtholic acid
      – Contains rigid chains of long, flat monomer units which are thought to undergo parallel ordering in the melt and form tightly packed fibrous chains in molded parts.
PET Chemical Structure and Applications

• The flexible, but short, (CH$_2$)$_2$ groups tend to leave the chains relatively stiff and PET is noted for its very slow crystallization. If cooled rapidly from the melt to a Temp below Tg, PET solidifies in amorphous form.

• If PET is reheated above Tg, crystallization takes place to up to 30%.

• In many applications PET is first pre-shaped in amorphous state and then given a uniaxial (fibers or tapes) or biaxial (film or containers) crystalline orientation.

• During Injection Molding PET can yield amorphous transparent objects (Cold mold) or crystalline opaques objects (hot mold)
PBT Chemical Structure and Applications

- The longer, more flexible (CH$_2$)$_4$ groups allow for more rapid crystallization than PET.
- PBT is not as conveniently oriented as PET and is normally injection molded.
- PBT has a sharp melting transition with a rather low melt viscosity.
- PBT has rapid crystallization and high degree of crystallization causing warpage concerns.
Thermoplastic Aromatic Copolyesters

• Polyarylesters
  – Repeat units feature only aromatic-type groups (phenyl or aryl groups) between ester linkages.
  – Called wholly aromatic polyesters
  – Based on a combination of suitable chemicals
    • p-hydroxybenzoic acid
    • terephthalic acid
    • isophthalic acid,
    • bisphenol-A
  – Properties correspond to a very stiff and regular chain with high crystallinity and high temperature stability
  – Applications include bearings, high temperature sensors, aerospace applications
  – Processed in injection molding and compression molding
  – Most thermoplastic LCP appear to be aromatic copolyesters
Applications for Polyesters (PET)

• Blow molded bottles
  – 100% of 2-liter beverage containers and liquid products

• Fiber applications
  – 25% of market in tire cords, rope, thread, cord, belts, and filter cloths.
  – Monofilaments- brushes, sports equipment, clothing, carpet, bristles
  – Tape form- uniaxially oriented tape form for strapping

• Film and sheets
  – photographic and x-ray films; biaxial sheet for food packages

• Molded applications- Reinforced PET [Rynite, Valox, Impet]
  – luggage racks, grille-opening panels, functional housings such as
    windshield wiper motors, blade supports, and end bells
  – sensors, lamp sockets, relays, switches, ballasts, terminal blocks

• Appliances and furniture
  – oven and appliance handles, coil forms for microwaves, and panels
    -- pedestal bases, seat pans, chair arms, and casters
Applications for Polyesters (PBT and LCP)

• PBT - 30 M lbs in 1988
• Molded applications (PBT) [Valox, Xenoy, Vandar, Pocan]
  – distributers, door panels, fenders, bumper fascias
  – automotive cables, connectors, terminal blocks, fuse holders and motor parts, distributor caps, door and window hardware
• Extruded applications
  – extrusion-coat wire
  – extruded forms and sheet produced with some difficulty
• Electronic Devices (LCP) [26 M lbs] [Terylene, Dacron, Kodel]
  – fuses, oxygen and transmission sensors
  – chemical process equipment and sensors
  – coil
# Mechanical Properties of Polyesters

<table>
<thead>
<tr>
<th>Mechanical Properties of polyester</th>
<th>PET</th>
<th>PBT</th>
<th>LCP Polyester</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cc</td>
<td>1.29-1.40</td>
<td>1.30 - 1.38</td>
<td>1.35 - 1.40</td>
</tr>
<tr>
<td>Crystallinity</td>
<td>10% - 30%</td>
<td>60%</td>
<td>&gt;80%</td>
</tr>
<tr>
<td>Molecular Weight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile Strength, psi</td>
<td>7,000 – 10,500</td>
<td>8,200</td>
<td>16,000 – 27,000</td>
</tr>
<tr>
<td>Tensile Modulus, psi</td>
<td>400K - 600K</td>
<td>280K – 435K</td>
<td>1,400K - 2,800K</td>
</tr>
<tr>
<td>Tensile Elongation, %</td>
<td>30% - 300%</td>
<td>50%-300%</td>
<td>1.3%-4.5%</td>
</tr>
<tr>
<td>Impact Strength ft-lb/in</td>
<td>0.25 - 0.70</td>
<td>0.7 - 1.0</td>
<td>2.4 - 10</td>
</tr>
<tr>
<td>CLTE $10^{-6}$ in/in/C</td>
<td>65</td>
<td>60-95</td>
<td>25-30</td>
</tr>
<tr>
<td>HDT 264 psi</td>
<td>70F -100F</td>
<td>122F - 185F</td>
<td>356F -671F</td>
</tr>
</tbody>
</table>
# Physical Properties of Polyester

<table>
<thead>
<tr>
<th>Optical</th>
<th>PET (Transparent to Opaque 245°C - 265°C)</th>
<th>PBT (Opaque 220°C – 267°C)</th>
<th>LCP Polyester (Opaque 400°C - 421°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tmelt</td>
<td></td>
<td>220°C – 267°C</td>
<td>400°C - 421°C</td>
</tr>
<tr>
<td>Tg</td>
<td>73°C - 80°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O Absorption</td>
<td>0.1 - 0.2% (24h)</td>
<td>0.085% (24h) 0.45% (Max)</td>
<td>&lt;0.1% (24h) &lt;0.1% (Max)</td>
</tr>
<tr>
<td>Oxidation Resistance</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>UV Resistance</td>
<td>Poor</td>
<td>Poor</td>
<td>none</td>
</tr>
<tr>
<td>Solvent Resistance</td>
<td>Attacked by halogen hydrocarbons Poor</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Alkaline Resistance</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>Acid Resistance</td>
<td>Poor</td>
<td>Poor</td>
<td>fair</td>
</tr>
<tr>
<td>Cost $/lb</td>
<td>$0.53</td>
<td>$1.48</td>
<td>$7.00 - $10.00</td>
</tr>
</tbody>
</table>
Advantages and Disadvantages of Polyesters

• Advantages
  – Tough and rigid
  – Processed by thermoplastic operations
  – Recycled into useful products as basis for resins in such applications as sailboats, shower units, and floor tiles
  – PET flakes from PET bottles are in great demand for fiberfill for pillows and sleeping bags, carpet fiber, geo-textiles, and regrind for injection and sheet molding
  – PBT has low moisture absorption

• Disadvantages
  – Subject to attack by acids and bases
  – Low thermal resistance
  – Poor solvent resistance
  – Must be adequately dried in dehumidifier prior to processing to prevent hydrolytic degradation.
Thermoplastic Copolyesters

• Copolyester is applied to those polyesters whose synthesis uses more than one glycol and/or more than one dibasic acid.

• Copolyester chain is less regular than monopolyester chain and as a result has less crystallinity

• PCTA copolyester (Poly cyclo-hexane-dimethanol-terephthalate acid) [amorphous]
  – Reaction includes cyclohexanediol and terephthalic acid with another acid substituted for a portion of the terephthalic acid
  – Extruded as transparent film or sheets that are suitable for packaging applications (frozen meats shrink bags, blister packages, etc..)

• Glycol-modified PET (PETG) [amorphous]
  – Blow-molded containers, thermoformed blister packages.
ABS, PC Background

- **ABS was invented during WWII as a replacement for rubber**
  - ABS is a terpolymer: acrylonitrile (chemical resistance), butadiene (impact resistance), and styrene (rigidity and processing ease)
  - Graft polymerization techniques are used to produce ABS
  - Family of materials that vary from high gloss to low matte finish, and from low to high impact resistance.
  - Additives enable ABS grades that are flame retardant, transparent, high heat-resistance, foamable, or UV-stabilized.

- **PC was invented in 1898 by F. Bayer in Germany**
  - Commercial production began in the US in 1959.
  - Amorphous, engineering thermoplastic that is known for toughness, clarity, and high-heat deflection temperatures.
  - Polycarbonates are linear, amorphous polyesters because they contain esters of carbonic acid and an aromatic bisphenol.
Acrylic and Cellulosic Background

• Acrylics (1901)
  – Includes acrylic and methacrylic esters, acids, and derivatives.
  – Used singularly or in combination with other polymers to produce products ranging from soft, flexible elastomers to hard, stiff thermoplastics and thermosets.

• Cellulosics (1883)
  – Cellulose nitrate was first developed in the 1880s.
  – First uses were billiard balls, combs, and photographic film.
  – Cellulose acetate was developed in 1927 reduced the limitations of flammability, and solvent requirement.
  – In 1923, CA became the first material to be injection molded.
  – Cellulose acetate butyrate (CAB) in 1938 and Cellulose acetate propionate (CAP) in 1945 found applications for hair brushes, toothbrushes, combs, cosmetic cases, hand tool handles, steering wheels, knobs, armrests, speakers, grilles, etc.
Acrylics Chemical Structure

- Acrylics - Basic formula

- Polymethyl acrylate

- Polymethyl methacrylate

-AcrylateStyreneAcrylonitrile (ASA)
**PS, PC, ABS Chemical Structure**

- **PS** (homopolymer -addition) - PC (condensation polymerization)
  atactic, amorphous

  ![PS Chemical Structure]

  ![PC Chemical Structure]

- **ABS** acrylonitrile butadiene styrene (Terpolymer- addition)

  ![ABS Chemical Structure]
Applications for PC and Acrylics

- **PC** (high impact strength, transparency, excellent creep and temperature)
  - lenses, films, windshields, light fixtures, containers, appliance components and tool housings
  - hot dish handles, coffee pots, popcorn popper lids, hair dryers.
  - Pump impellers, safety helmets, beverage dispensers, trays, signs
  - aircraft parts, films, cameras, packaging

- **Acrylics**
  - Optical applications, outdoor advertising signs, aircraft windshields, cockpit covers, bubble bodies for helicopters
  - Plexiglass, window frames, (glass filled): tubs, counters, vanities
# Mechanical Properties of Acrylic, PC, PC/ABS

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>Acrylic</th>
<th>PC</th>
<th>ABS</th>
<th>PC/ABS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cc</td>
<td>1.16-1.19</td>
<td>1.2</td>
<td>1.16-1.21</td>
<td>1.07 - 1.15</td>
</tr>
<tr>
<td>Tensile Strength, psi</td>
<td>5,000 - 9,000</td>
<td>9,500</td>
<td>3,300 - 8,000</td>
<td>5,800 - 9,300</td>
</tr>
<tr>
<td>Tensile Modulus, psi</td>
<td>200K – 500K</td>
<td>350 K</td>
<td>320K-400K</td>
<td>350K -450K</td>
</tr>
<tr>
<td>Tensile Elongation, %</td>
<td>20 - 70%</td>
<td>110%</td>
<td>1.5%-25%</td>
<td>50%-60%</td>
</tr>
<tr>
<td>Impact Strength ft-lb/in</td>
<td>0.65 -2.5</td>
<td>16</td>
<td>1.4-12</td>
<td>6.4 - 11</td>
</tr>
<tr>
<td>Hardness</td>
<td>M38-M68</td>
<td>M70</td>
<td>R100-120</td>
<td>R95 -R120</td>
</tr>
<tr>
<td>CLTE $10^{-6}$ mm/mm/C</td>
<td>48 - 80</td>
<td>68</td>
<td>65- 95</td>
<td>67</td>
</tr>
<tr>
<td>HDT (°F)</td>
<td>165-209F</td>
<td>270</td>
<td>190F - 225F</td>
<td>225F</td>
</tr>
</tbody>
</table>
# Physical Properties of Acrylic, PC, PC/ABS

<table>
<thead>
<tr>
<th></th>
<th>Acrylic</th>
<th>PC</th>
<th>ABS</th>
<th>PC/ABS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optical</strong></td>
<td>Transparent</td>
<td>Transparent</td>
<td>Transparent</td>
<td>Transparent</td>
</tr>
<tr>
<td><strong>Tmelt</strong></td>
<td>105°C</td>
<td>150°C</td>
<td>125°C</td>
<td>135°C</td>
</tr>
<tr>
<td><strong>Tg</strong></td>
<td>75°C to 105°C</td>
<td>110°C to 125°C</td>
<td>110°C to 125°C</td>
<td>120°C</td>
</tr>
<tr>
<td><strong>H₂O Absorption</strong></td>
<td>0.01-0.03% (24h)</td>
<td>0.2-0.6% (24h)</td>
<td>0.2-0.6% (24h)</td>
<td>0.15-0.25% (24h)</td>
</tr>
<tr>
<td><strong>Oxidation Resistance</strong></td>
<td>good</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td><strong>UV Resistance</strong></td>
<td>fair</td>
<td>fair</td>
<td>fair</td>
<td>fair</td>
</tr>
<tr>
<td><strong>Solvent Resistance</strong></td>
<td>Soluble in Acetone, Benzene, Toluene, Ethylene dichloride</td>
<td>Partially Soluble in Acetone, Benzene, Toluene. Dissolves in hot benzene-toluene</td>
<td>Soluble in Toluene and Ethylene dichloride, Partially in Benzene</td>
<td>Soluble in Toluene and Ethylene dichloride, Partially in Benzene</td>
</tr>
<tr>
<td><strong>Alkaline Resistance</strong></td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Poor: attacked by oxidizing agents</td>
</tr>
<tr>
<td><strong>Acid Resistance</strong></td>
<td>Poor: attacked by oxidizing agents</td>
<td>Poor: attacked by oxidizing agents</td>
<td>Poor: attacked by oxidizing agents</td>
<td>good</td>
</tr>
<tr>
<td><strong>Cost $/lb</strong></td>
<td>$0.41</td>
<td>$0.90</td>
<td>$0.90</td>
<td>$0.87</td>
</tr>
</tbody>
</table>
Advantages

• PC
  – High impact strength, excellent creep resistance, transparent
  – Very good dimensional stability and continuous temp over 120 C

• Acrylics
  – Optical clarity, weatherability, electrical properties, rigid, high gloss

Disadvantages

• PC
  – High processing temp, UV degradation
  – Poor resistance to alkalines and subject to solvent cracking

• Acrylics
  – Poor solvent resistance, stress cracking, combustibility, Use T 93C
Other Crystalline Thermoplastics

Reference: Appendix E. Industrial Plastics

• PEEK
  – History
  – Chemistry and Chemical Structure
  – Applications
  – Mechanical Properties
  – Physical Properties
  – Processing Characteristics
  – Advantages/Disadvantages

• PPO and PPS

• Review

• Questions
PEEK History

- Polyether-ether-ketone (PEEK) and Polyether ketone (PEK)
- PEEK invented by ICI in 1982. PEK introduced in 1987
- PEEK and PEK are aromatic polyketones
- Volume for polyketones is 500,000 lbs per year in 1990. Estimated to reach 3 to 4 million by 2000.
- Cost is $30 per pound (as of October 1998)
- Product Names
  - ICI: Vivtrex
  - BASF: Ultrapak
  - Hoechst Celanese: Hostatec
  - DuPont: PEKK
  - Amoco: Kadel
Chemistry & Chemical Structure

- PEEK- Poly-ether-ether-ketone

\[
\begin{array}{c}
\text{O} \\
\text{-} \\
\text{O} \\
\text{O}
\end{array}
\begin{array}{c}
\text{C} \\
\text{C}
\end{array} \quad \text{n}
\]

- PEK- Poly-ether-ketone

\[
\begin{array}{c}
\text{O} \\
\text{-} \\
\text{O} \\
\text{O}
\end{array} \\
\begin{array}{c}
\text{C} \\
\text{C}
\end{array} \quad \text{n}
\]
Chemical Synthesis

• Synthesis of polyketones
  – **PEK**: Formation of the **carbonyl** link by polyaroylation from low cost starting materials. Requires solvents such as liquid HF. Excessive solvents and catalyst cause the high material cost.

\[
\begin{align*}
\text{PEK} \quad & \quad \text{O} \quad \text{C} \quad \text{Cl} \\
& \xrightarrow{\text{HF, catalyst}} \quad \left[ \begin{array}{c}
\text{O} \\
\text{C} \\
\end{array} \right]_n + \text{HCl} + \text{CO}_2 + \text{H}_2\text{O}
\end{align*}
\]

– **PEEK**: Formation of **ether** link using phenoxide anions to displace activated halogen.

\[
\begin{align*}
\text{PEEK} \quad & \quad \text{O} \\
& \xrightarrow{\text{K}_2\text{CO}_3, \text{DPS}} \quad \text{F} \quad \text{C} \quad \text{F} + \text{OH} \quad \text{OH} \\
& \quad \text{PEEK} + \text{CO}_2 + \text{H}_2\text{O} + \text{KF}
\end{align*}
\]
PEEK and PEK Applications

• Aerospace: replacement of Al
  – Fuel line brakes to replacement of primary structure

• Electrical
  – wire coating for nuclear applications, oil wells, flammability-critical mass transit.
  – Semi-conductor wafer carriers which can show better rigidity, minimum weight, and chemical resistance to fluoropolymers.

• Other applications
  – Chemical and hydrolysis resistant valves (replaced glass)
  – Internal combustion engines (replaced thermosets)
  – Cooker components (replaced enamel)
  – Automotive components (replaced metal)
  – High temperature and chemical resistant filters from fiber
  – Low friction bearings
# Mechanical Properties of PEEK

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>PEEK</th>
<th>LCP Polyester</th>
<th>Nylon 6,6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cc</td>
<td>1.30-1.32</td>
<td>1.35 - 1.40</td>
<td>1.13-1.15</td>
</tr>
<tr>
<td>Tensile Strength, psi</td>
<td>10,000 – 15,000</td>
<td>16,000 – 27,000</td>
<td>14,000</td>
</tr>
<tr>
<td>Tensile Modulus, psi</td>
<td>500K</td>
<td>1,400K - 2,800K</td>
<td>230K – 550K</td>
</tr>
<tr>
<td>Tensile Elongation, %</td>
<td>30% - 150%</td>
<td>1.3%-4.5%</td>
<td>15%-80%</td>
</tr>
<tr>
<td>Impact Strength, ft-lb/in</td>
<td>0.6 – 2.2</td>
<td>2.4 - 10</td>
<td>0.55 – 1.0</td>
</tr>
<tr>
<td>Hardness</td>
<td>R120</td>
<td>R124</td>
<td>R120</td>
</tr>
<tr>
<td>CLTE $10^{-6}$ mm/mm/C</td>
<td>40 - 47</td>
<td>25-30</td>
<td>80</td>
</tr>
<tr>
<td>HDT 264 psi</td>
<td>320 F</td>
<td>356F - 671F</td>
<td>180F</td>
</tr>
</tbody>
</table>
### Physical Properties of PEEK

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>PEEK</th>
<th>LCP Polyester</th>
<th>Nylon 6,6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical</td>
<td>Opaque</td>
<td>Opaque</td>
<td>Translucent to opaque</td>
</tr>
<tr>
<td>Tmelt</td>
<td>334 C</td>
<td>400 C</td>
<td>255C – 265C</td>
</tr>
<tr>
<td>Tg</td>
<td>177 C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O Absorption</td>
<td>0.1-0.14% (24h)</td>
<td>0.1% (24h)</td>
<td>1.0-2.8% (24h)</td>
</tr>
<tr>
<td></td>
<td>0.5% (Max)</td>
<td>0.1% (Max)</td>
<td>8.5% (Max)</td>
</tr>
<tr>
<td>Oxidation Resistance</td>
<td>good</td>
<td>Good</td>
<td>good</td>
</tr>
<tr>
<td>UV Resistance</td>
<td>Poor</td>
<td>good</td>
<td>Poor</td>
</tr>
<tr>
<td>Solvent Resistance</td>
<td>good</td>
<td>good</td>
<td>Dissolved by phenol &amp; formic acid</td>
</tr>
<tr>
<td>Alkaline Resistance</td>
<td>good</td>
<td>Poor</td>
<td>Resistant</td>
</tr>
<tr>
<td>Acid Resistance</td>
<td>good</td>
<td>fair</td>
<td>Poor</td>
</tr>
<tr>
<td>Cost $/lb</td>
<td>$30</td>
<td>$7 - $10</td>
<td>$1.30</td>
</tr>
</tbody>
</table>
# Properties of Reinforced PEEK

<table>
<thead>
<tr>
<th>Mechanical Properties Reinforced</th>
<th>PEEK</th>
<th>PEEK 30% glass fibers</th>
<th>PEEK with 30% carbon fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cc</td>
<td>1.30-1.32</td>
<td>1.52</td>
<td>1.43</td>
</tr>
<tr>
<td>Tensile Strength, psi</td>
<td>10,000 – 15,000</td>
<td>23,000 – 29,000</td>
<td>31,000</td>
</tr>
<tr>
<td>Tensile Modulus, psi</td>
<td>500K</td>
<td>1,300K – 1,600K</td>
<td>1,900K – 3,500K</td>
</tr>
<tr>
<td>Tensile Elongation, %</td>
<td>30% - 150%</td>
<td>2%-3%</td>
<td>1% - 4%</td>
</tr>
<tr>
<td>Impact Strength ft-lb/in</td>
<td>1.6</td>
<td>2.1 – 2.7</td>
<td>1.5 – 2.1</td>
</tr>
<tr>
<td>Hardness</td>
<td>R120</td>
<td>R120</td>
<td></td>
</tr>
<tr>
<td>CLTE $10^{-6}$ mm/mm/C</td>
<td>40 - 47</td>
<td>12-22</td>
<td>15-22</td>
</tr>
<tr>
<td>HDT 264 psi</td>
<td>320 F</td>
<td>550F -600F</td>
<td>550F -610F</td>
</tr>
</tbody>
</table>
# Processing Properties of PEEK

<table>
<thead>
<tr>
<th>Processing Properties</th>
<th>PEEK</th>
<th>LCP Polyester</th>
<th>Nylon 6,6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tmelt</td>
<td>334 C</td>
<td>400 C - 420 C</td>
<td>255C – 265C</td>
</tr>
<tr>
<td></td>
<td>E: 660F – 725F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molding Pressure</td>
<td>10 -20 kpsi</td>
<td>5 - 16 kpsi</td>
<td>1 -20 kpsi</td>
</tr>
<tr>
<td>Mold (linear) shrinkage (in/in)</td>
<td>0.011</td>
<td>0.001 – 0.008</td>
<td>0.007 – 0.018</td>
</tr>
</tbody>
</table>
Advantages and Disadvantages of Polyketones

• Advantages
  – Very high continuous use temperature (480F)
  – Outstanding chemical resistance
  – Outstanding wear resistance
  – Excellent hydrolysis resistance
  – Excellent mechanical properties
  – Very low flammability and smoke generation
  – Resistant to high levels of gamma radiation

• Disadvantages
  – High material cost
  – High processing temperatures
Polyphenylene Materials

• Several plastics have been developed with the benzene ring in the backbone
  » Polyphenylene
  » Polyphenylene oxide (amorphous)
  » Poly(phenylene sulfide) (crystalline)
  » Polymonochloroparaxylylene
PPO and PPS Materials

*Advantages of PPS
- Usage Temp at 450F
- Good radiation resistance
- Excellent dimensional stability
- Low moisture absorption
- Good solvent and chemical resistance
- Excellent abrasion resistance

*Advantages of PPO
- Good fatigue and impact strength
- Good radiation resistance
- Excellent dimensional stability
- Low oxidation

*Disadvantages of PPS
- High Cost
- High process temperatures
- Poor resistance to chlorinated hydrocarbons

*Disadvantages of PPO
- High cost
- Poor resistance to certain chemicals
PPO and PPS Applications

*PPS Applications
- Computer components
- Range components
- Hair dryers
- Submersible pump enclosures
- Small appliance housings

*PPO Applications
- Video display terminals
- Pump impellers
- Small appliance housings
- Instrument panels
- Automotive parts
# PPS and PPO Mechanical Properties

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>PPS</th>
<th>PPO</th>
<th>Nylon 6,6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cc</td>
<td>1.30</td>
<td>1.04 – 1.10</td>
<td>1.13-1.15</td>
</tr>
<tr>
<td>Tensile Strength, psi</td>
<td>9,500</td>
<td>7,800</td>
<td>14,000</td>
</tr>
<tr>
<td>Tensile Modulus, psi</td>
<td>480K</td>
<td>360K</td>
<td>230K – 550K</td>
</tr>
<tr>
<td>Tensile Elongation, %</td>
<td>1% - 2%</td>
<td>60% - 400%</td>
<td>15%-80%</td>
</tr>
<tr>
<td>Impact Strength ft-lb/in</td>
<td>&lt; 0.5</td>
<td>4 - 6</td>
<td>0.55 – 1.0</td>
</tr>
<tr>
<td>Hardness</td>
<td>R123</td>
<td>R115</td>
<td>R120</td>
</tr>
<tr>
<td>CLTE (10^{-6}) mm/mm/C</td>
<td>49</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>HDT 264 psi</td>
<td>275 F</td>
<td>118F -210F</td>
<td>180 F</td>
</tr>
</tbody>
</table>
## PPS and PPO Physical Properties

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>PPS</th>
<th>PPO</th>
<th>Nylon 6,6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical</td>
<td>Opaque</td>
<td>Opaque</td>
<td>Translucent to opaque</td>
</tr>
<tr>
<td>Tmelt</td>
<td>290 °C</td>
<td>250 °C</td>
<td>255 °C – 265 °C</td>
</tr>
<tr>
<td>Tg</td>
<td>88 °C</td>
<td>110 – 140 °C</td>
<td></td>
</tr>
<tr>
<td>H₂O Absorption</td>
<td>&gt; 0.02% (24h)</td>
<td>0.01% (24h)</td>
<td>1.0-2.8% (24h) 8.5% (Max)</td>
</tr>
<tr>
<td>Oxidation Resistance</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>UV Resistance</td>
<td>fair</td>
<td>fair</td>
<td>Poor</td>
</tr>
<tr>
<td>Solvent Resistance</td>
<td>Poor in aromatics</td>
<td>Poor in aromatics</td>
<td>Dissolved by phenol &amp; formic acid</td>
</tr>
<tr>
<td>Alkaline Resistance</td>
<td>good</td>
<td>good</td>
<td>Resistant</td>
</tr>
<tr>
<td>Acid Resistance</td>
<td>poor</td>
<td>good</td>
<td>Poor</td>
</tr>
<tr>
<td>Cost $/lb</td>
<td>$2</td>
<td>$1.80</td>
<td>$1.30</td>
</tr>
</tbody>
</table>
PPS and PPO Processing Properties

<table>
<thead>
<tr>
<th>Processing Properties</th>
<th>PPS</th>
<th>PPO</th>
<th>Nylon 6,6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tmelt</td>
<td>290 C</td>
<td>250 C</td>
<td>255C – 265C</td>
</tr>
<tr>
<td>Recommended Temp Range</td>
<td>I: 600F – 625F</td>
<td>I: 400F – 600F</td>
<td>I: 500F – 620F</td>
</tr>
<tr>
<td>Molding Pressure</td>
<td>5 – 15 kpsi</td>
<td>12 - 20 kpsi</td>
<td>1 -20 kpsi</td>
</tr>
<tr>
<td>Mold (linear) shrinkage (in/in)</td>
<td>0.007</td>
<td>0.012 – 0.030</td>
<td>0.007 – 0.018</td>
</tr>
</tbody>
</table>

• PPS frequently has glass fibers loaded up to 40% by weight
  » Tensile strength = 28 kpsi, tensile modulus = 2 Mpsi, HDT = 500F

• PPO is frequently blended with PS over a wide range of percentages. (Noryl from G.E.)
Section Review

- PEEK and PEK are aromatic polyketones.
- Ketone groups have R - O - R functionality.
- Chemical structure of PEEK and PEK depicts benzene - oxygen - benzene in backbone.
- PEEK and PEK are used primarily in applications requiring high temperature use and chemical resistance.
- AP2C is a special version of PEEK with 68% continuous carbon fiber.
- Polyphenylene materials are plastics with the benzene ring in the backbone.
- PPO and PPS are characterized as heterochain thermoplastics, which has atoms other than C in the chain.
- PPO and PPS are made via Condensation Polymerization.
- PPS frequently has glass fibers loaded up to 40% by weight.
- PPO is frequently blended with PS over a wide range of percentages.
Homework Questions

1. Define PEEK, PPO and PPS chemical structures.

2. How are the properties of PEEK and PPS alike?

3. Density of PEEK is _____, PPS is _____ , and PPO is _____ , which is higher/lower than PBT and nylon?

4. What is the tensile strength of PEEK with 0%, 30% glass fibers? What is the tensile modulus?

5. Plot tensile strength and tensile modulus of PEEK, PPO, PPS, PET, PBT, Nylon 6, PP, LDPE and HDPE to look like the following
Homework Questions

6. Four typical Physical Properties of PEEK are Optical = _______, Resistance to moisture= ______ , UV resistance= _____, acid resistance=_______

7. The Advantages of PEEK are ________, ________, ________, and __________.

8. The Disadvantages of PEEK are ________, ________, ________, and __________.

9. How are the properties of PPO and PPS alike? How are they different?

10. What are 3 advantages that Nylon has over PPO and PPS? ________________________________

______________________________________________
Section Review

- Polyesters is one of many heterochain thermoplastics, which has atoms other than C in the chain.
- Polyesters includes unsaturated (thermosets), saturated and aromatic thermoplastic polyesters.
- Condensation polymerization for Polyester

- Thermoplastic polyesters have ester(-C-O) repeating link
- Linear and aromatic polyesters
- Most thermoplastic LCP appear to be aromatic copolyesters
- Effects of reinforcements on polyester
- Effects of moisture environment on nylon
- If cooled rapidly from the melt to a Temp below Tg, PET solidifies in amorphous form. If reheated PET acquires 30% crystallinity
- PET has rigid group of \((\text{CH}_2)_2\); PBT has more flexible \((\text{CH}_2)_4\)
- Copolyester chain is less regular than monopolyester chain and as a result has less crystallinity
Homework Questions

1. Define PBT and PET chemical structure.
2. Why was Carothers not successful in developing polyesters?
3. Density of PET is _____ which is higher/lower than PBT and nylon?
4. What is the tensile strength of PET with 0%, 30% glass fibers? What is the tensile modulus?
5. Plot tensile strength and tensile modulus of PET, PBT, Nylon 6, PP, LDPE and HPDE to look like the following
Homework Questions

6. Four typical Physical Properties of Polyester are Optical = ________, Resistance to moisture= ________, UV resistance= ________, acid resistance= ________

7. The Advantages of Polyester are ________, ________, ________, and ________.

8. The Disadvantages of Polyester are ________, ________, ________, and ________.

9. Glass fiber affects Polyester by (strength) ________, (modulus)_______, (elongation)_______, (density) ________ and (cost) ________.

10. What affect does the copolymer have on the crystallinity of polyesters and why? _________________________________________________________________. 
Homework Questions

1. Define Nylon 6,6 and Nylon 6 and Nylon 6,12 chemical structure
2. If MW of PA is 50,000, what is the approx. DP?
3. Density of PA is _____ which is higher/lower than PP.
4. What is the tensile strength of nylon 6,6 with 0%, 30% glass fibers? What is the tensile modulus?
5. Plot tensile strength and tensile modulus of Nylon 6, PP, LDPE and HPDE to look like the following
Homework Questions

6. Four typical Physical Properties of PA are Optical = _______, Resistance to moisture= ______, UV resistance= _____, solvent resistance=________

7. The Advantages of PA are __________, __________, __________, and __________.

8. The Disadvantages of PP are __________, __________, __________, and __________.

9. Glass fiber affects PA by (strength) ________, (modulus)________, (impact)_______, (density) __________, and (cost) ____________.

10. Two Aromatic PA are ____________, and ____________.