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Chapter 7: Polymers Manufacturing

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Outline

I Polymers

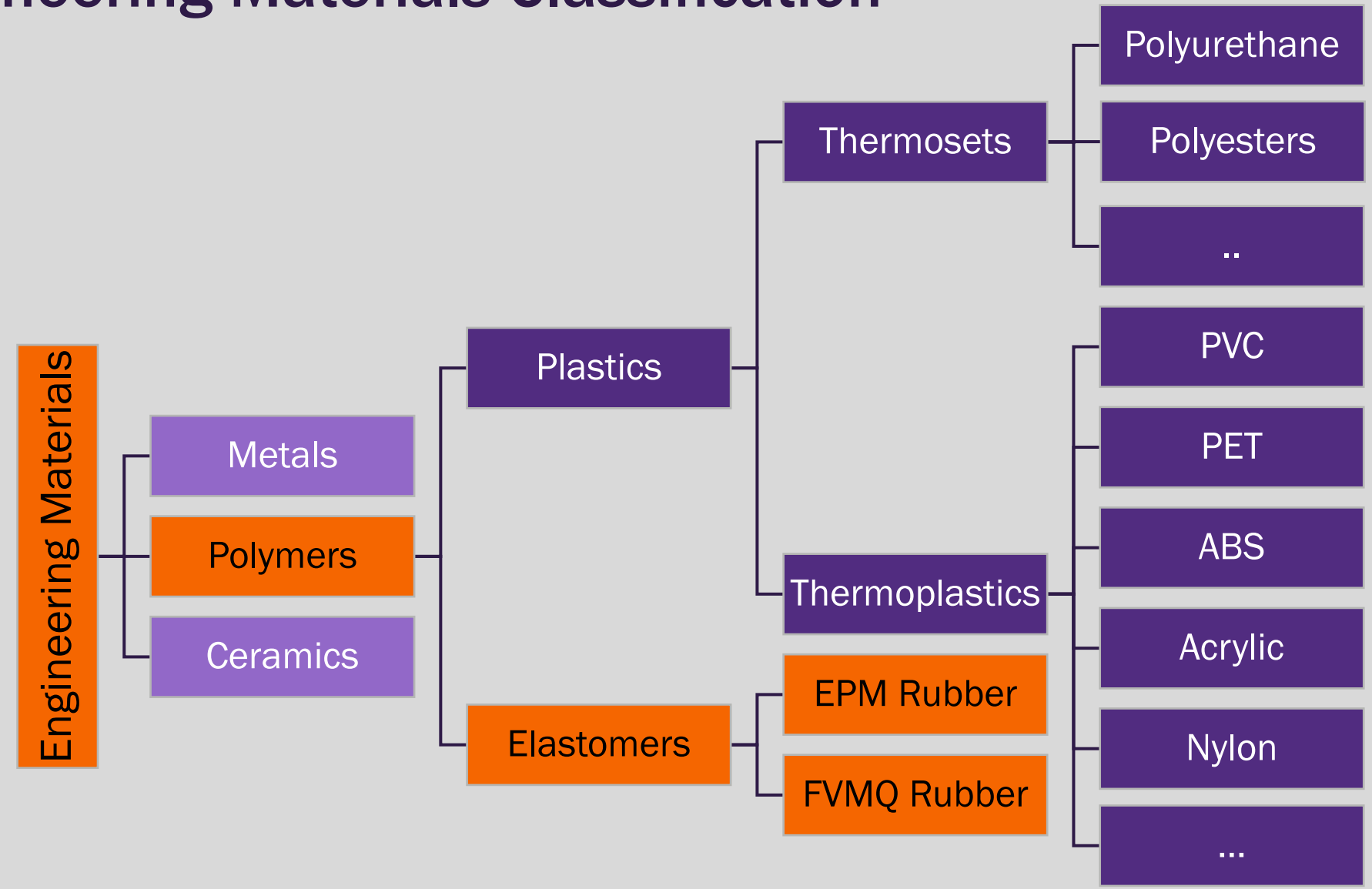
II Polymerization

III Injection Molding

IV Extrusion Molding

V Blow Molding

Engineering Materials Classification

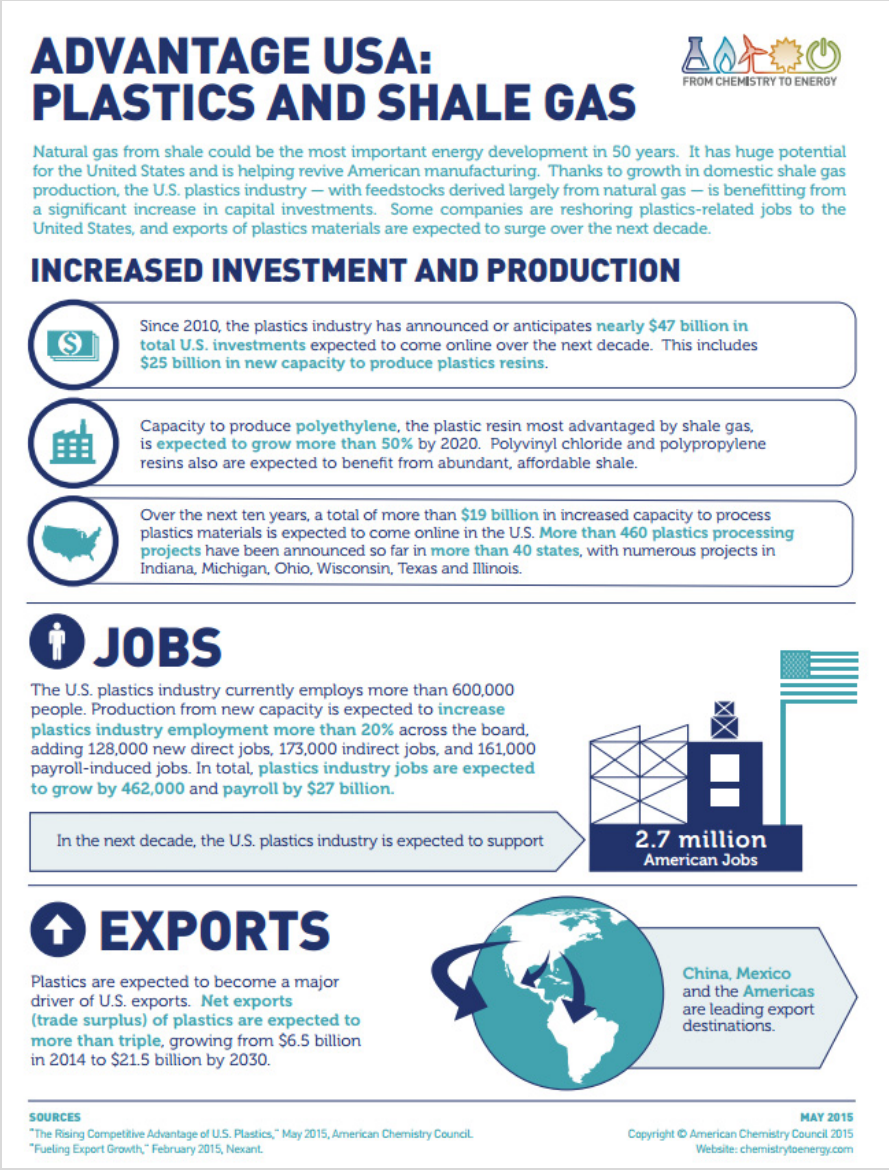


Origin of Polymer Raw Materials

- Wide range of natural and synthetic polymers.
- Natural polymers exist in flora and fauna. They include proteins, cellulose, and natural rubber.
- Synthetic polymers are derived mainly from mineral oil, natural gas, and coal. They include among others nylon, polyethylene, phenolics, and epoxies.

Polymers Manufacturing Economics

- Almost every item contains polymers: Television, Car, Airplane, Medical, Furniture, Packages, Kitchen utensils… [1]
- The ease of recycling and shaping, made polymer gain the lion share of the manufactured materials
- Since 2010, the plastics industry has invested nearly $47 billion in US
- Over 460 plastics processing projects have been announced in the US
- Net plastic exports are expected to grown from $6.5 billion in 2014 to $21.5 billion in 2030

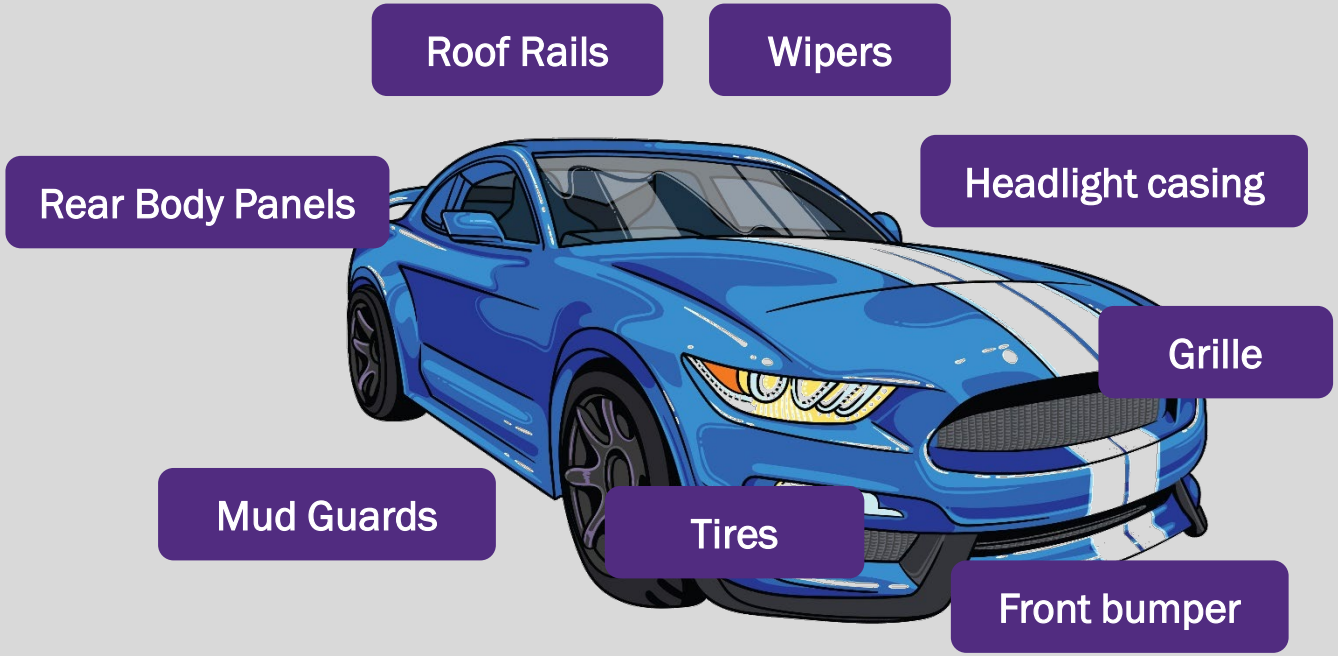


[1] www.americanchemistry.com

Evolution of Polymers Manufacturing

- Earliest written account around 12th century by Horner's Company of London, with tortoiseshell and horn as the early natural polymer products.
- In 1868, John Wesley Hyatt mixed pyroxylin (cotton – nature's polymeric) and nitric acid with camphor to create celluloid. Originally as a substitute for ivory billiard balls
- In 1872, Hyatt Brothers invented first polymer injection molding machine
- In 1881 patent on photographic film (sold to Eastman – Kodak in 1889)
- In 1946, first extrusion screw injection machine invented by James Henry

Growth of Applications - Automotive



Almost no plastic found in cars from 1950 and before like this 1954 Mercedes Benz 300SL Gullwing

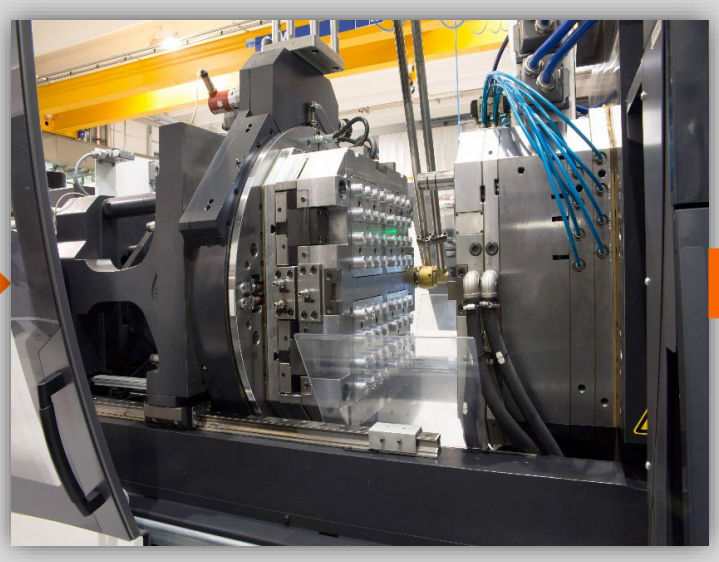
Today, cars have large amounts of polymer parts built in (~260lb) due to comparable light weight, material properties, economics, etc.

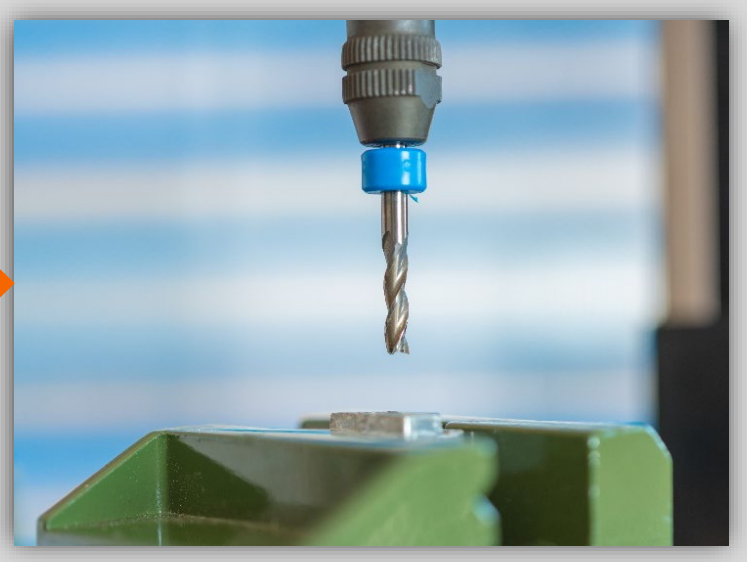
“Plastic Cars”

- East German **Trabant** car (1955-1991)
- Body made of ‘Duroplast’, a thermoset plastic

- BMW **i3** car (2013-today)
- Body made of carbon fiber-reinforced plastics

Polymers Manufacturing Steps





Mixing

- Starting material is powder or pellets
- Material is melted and rendered in a viscous state
- Additives are added if needed (e.g., colorants)

Forming

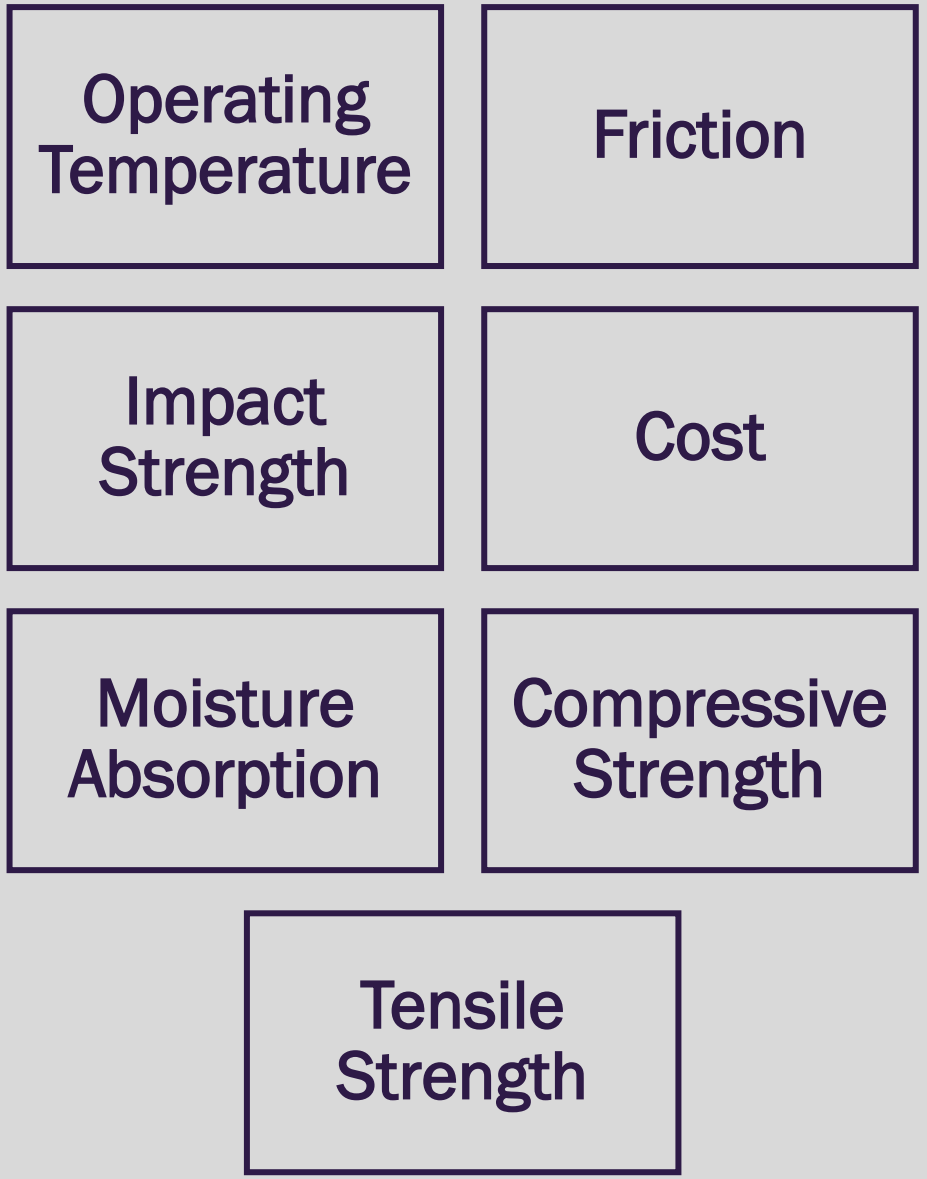
- Selection of forming process
- Understanding of 2D manufacturing (Extrusion) vs. 3D manufacturing (Injection, Blow)

Finishing

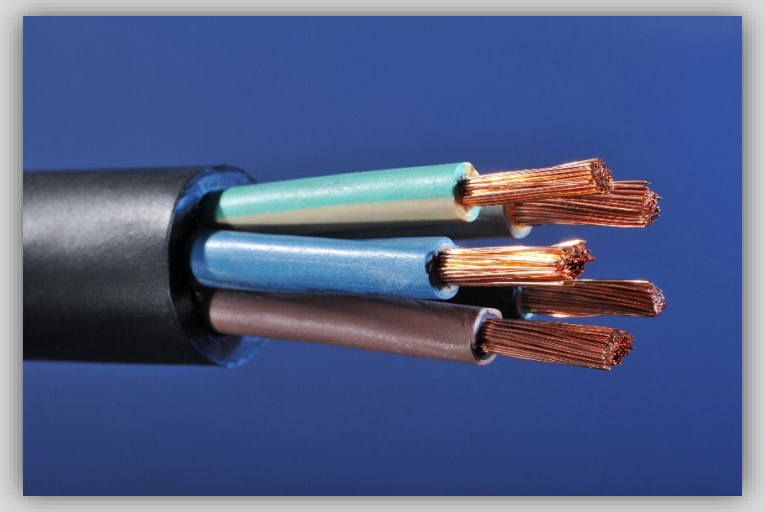
- Post manufacturing machining
- Assembly of multiple components

Polymer Properties

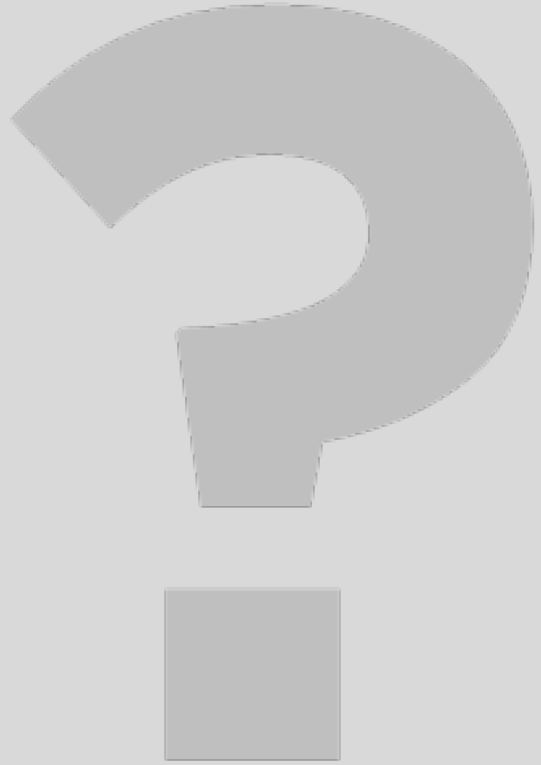
- Polymers have highly desired properties such as corrosion resistance, electrical insulation and cost
- However, with the exception of advanced polymers, they lack strength needed for some engineering applications
- Polymer constitute an excellent matrix element in the manufacturing of composites
  - Traditionally, thermoset is used as a primary prepreg resin system
  - Recent research evolves around usage of thermoplastic as matrix, but it is still not common



Applications



Knowledge Check



What is the Basic Polymers Manufacturing Sequence?

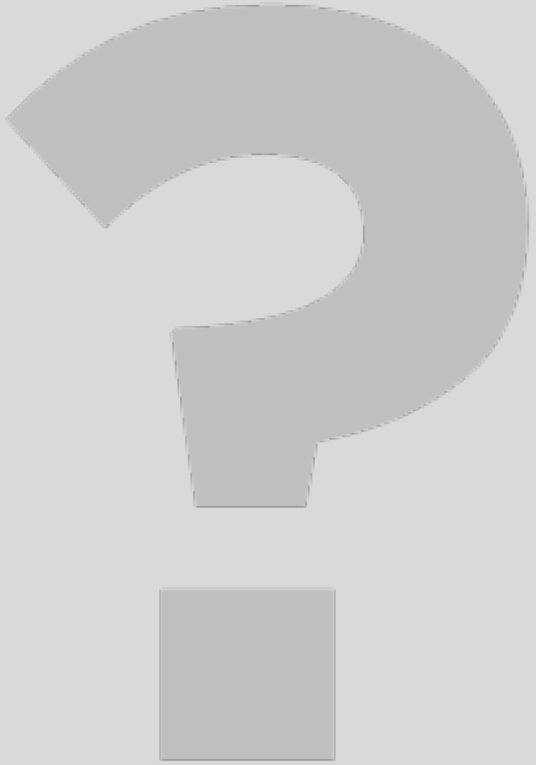
A. Mixing, Forming, Finishing
B. Forming, Mixing, Treatment
C. Finishing, Treatment, Mixing

Knowledge Check

What is the Basic Polymers Manufacturing Sequence?

A. **Mixing, Forming, Finishing**
B. Forming, Mixing, Treatment
C. Finishing, Treatment, Mixing

Knowledge Check



Composite Matrix Material is Mainly…

A. Thermoset
B. Thermoplastic
C. Elastomer

Knowledge Check

Composite Matrix Material is Mainly…

A. Thermoset
B. Thermoplastic
C. Elastomer

Efforts are made to make thermoplastic more commonly used.

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Polymers

Section I

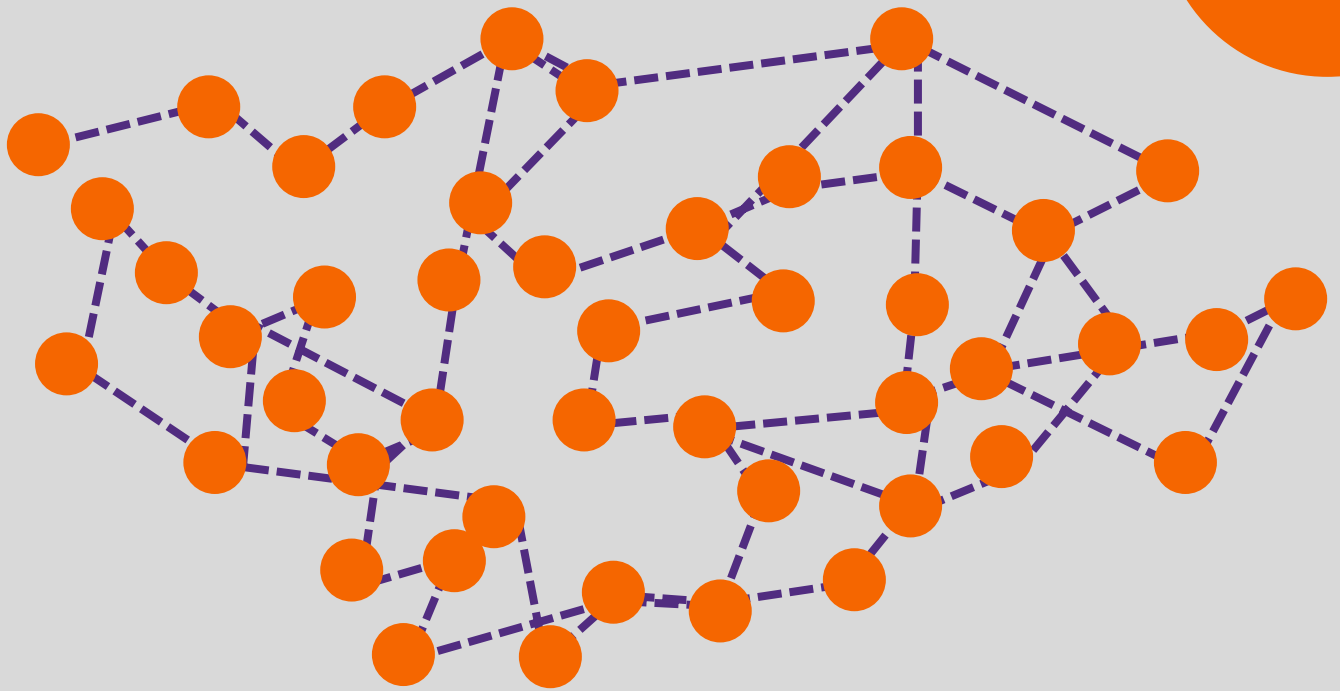
What is a Polymer?

polymer

=

polus + meros

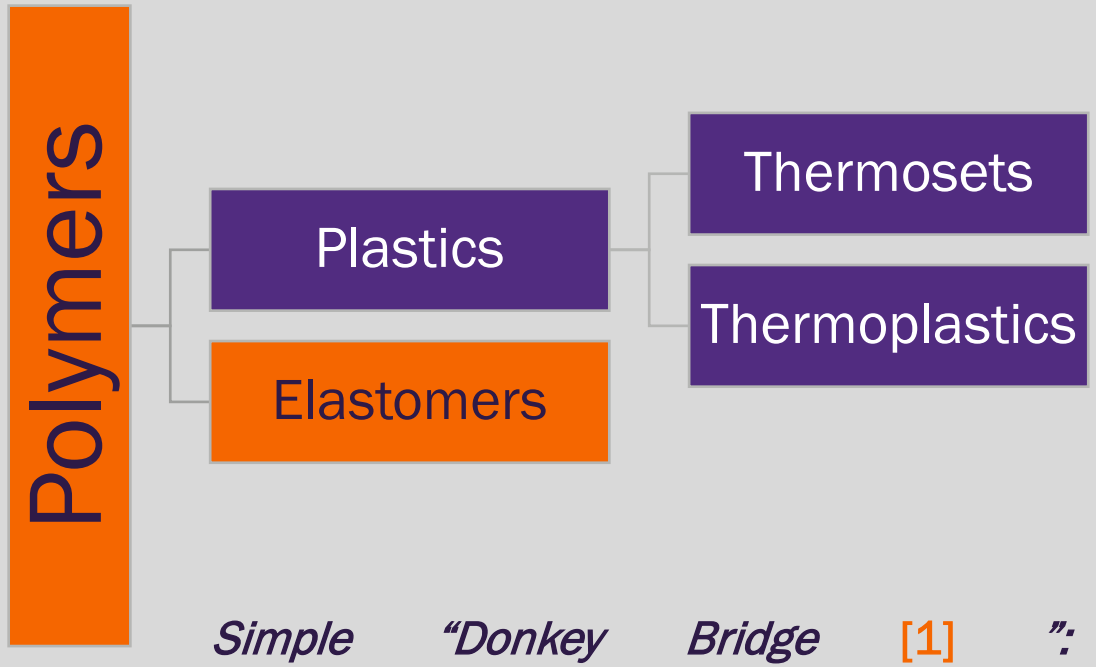
many parts



Monomer

Types of Polymers

- Polymers are split into three groups
- The split is aligned with the polymerization method used to create the polymer out of several monomers
- The molecular structure of the polymer is a clear indication to the type of the polymer and will be introduced later
- Polymers can be split into
  - Thermoplastics,
  - Thermosets and
  - Elastomers
- Thermoplastics and Thermosets are often referred to as plastics



Simple "Donkey Bridge [1] ": Thermoplastics (Butter) and Thermosets (Bread)

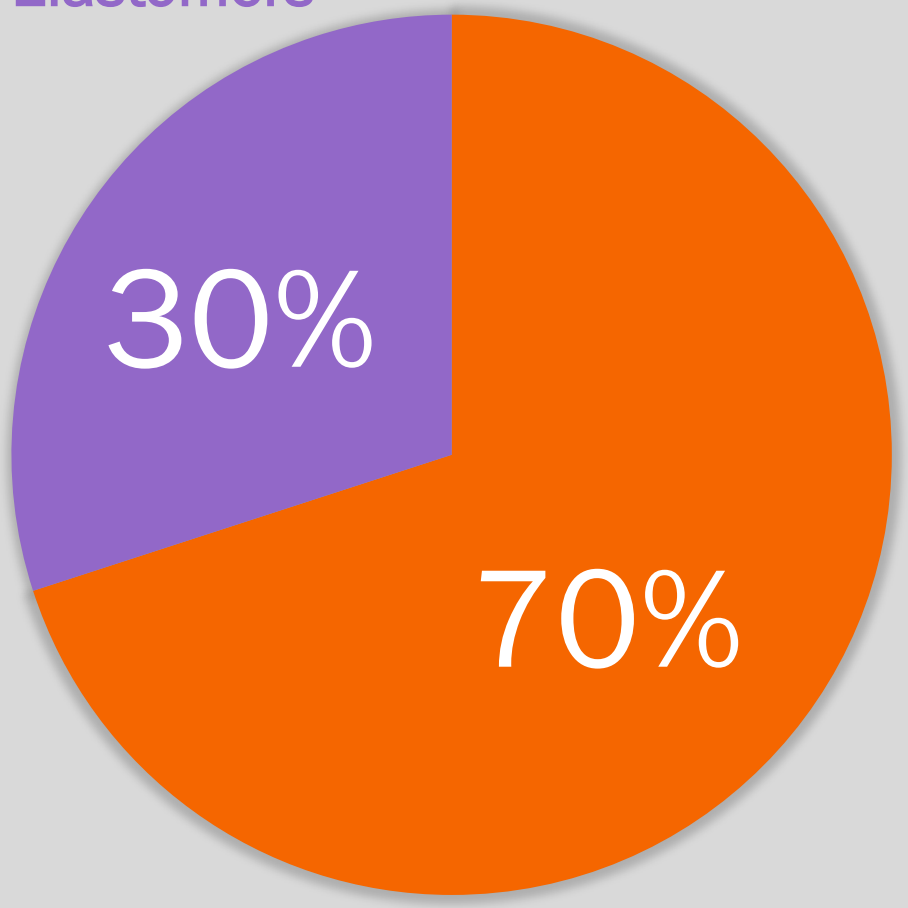
[1] http://thegermanstandard.com/2014/05/18/having-trouble-remembering-words-a-donkey-bridge-might-help/

Thermoplastic Polymers

- Thermoplastic polymers are the most prominent and they hold the biggest market share of polymers
- The fundamental concept of thermoplastic polymers is that they can be subjected to multiple heating and cooling cycles with minimal degradation
- This is what makes them desirable as an application material, since they can be recycled
- Thermoplastics are Thermo+Plastic to emphasize on the effect/ability to absorb the thermal variation
- Typically, we add plasticizers to reduce the brittleness of the thermoplastic polymer

TP: Market Share

- Thermoplastics are commercially the most important of the three types of polymers
- On a volumetric basis, current annual usage of polymers exceeds that of metals
- While thermoplastic (TP) are in their solid state at room temperature, they transform into a liquid upon heating
- Most TP require low amount of heating for the transformation process



TP: Recycling

- The Society of Plastics Industry (SPI) created codes for easy recycling of plastics
- They can be found on any thermoplastic part (Check out your water bottle!)
- The codes stand for:
  - PET/PETE
  - HDPE
  - PVC
  - LDPE
  - PP
  - PS
- The code 7 is reserved for all other TP not listed above

TP: Prominent Applications

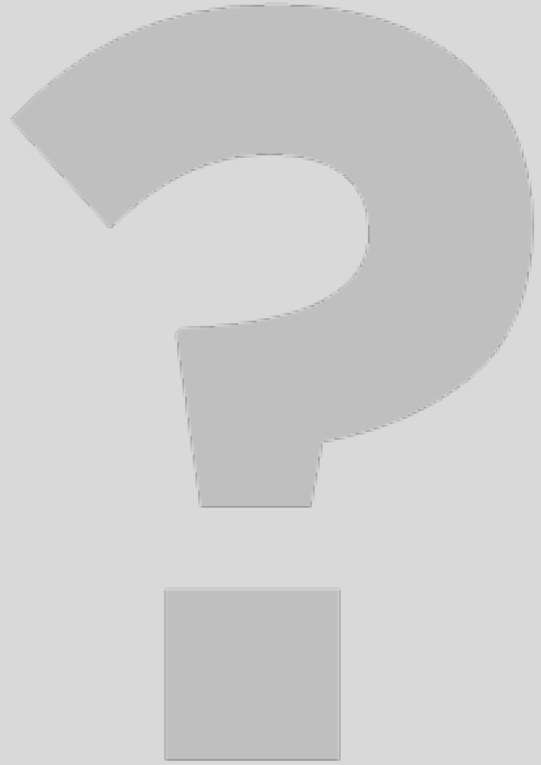
PVC

Polyethylene

Polystyrene

Polypropylene

Knowledge Check



Why Did the SPI Label Plastics?

A. To indicate how they are manufactured
B. To indicate design properties
C. To indicate the operating temperature range
D. To facilitate recycling
E. To facilitate sales

Knowledge Check

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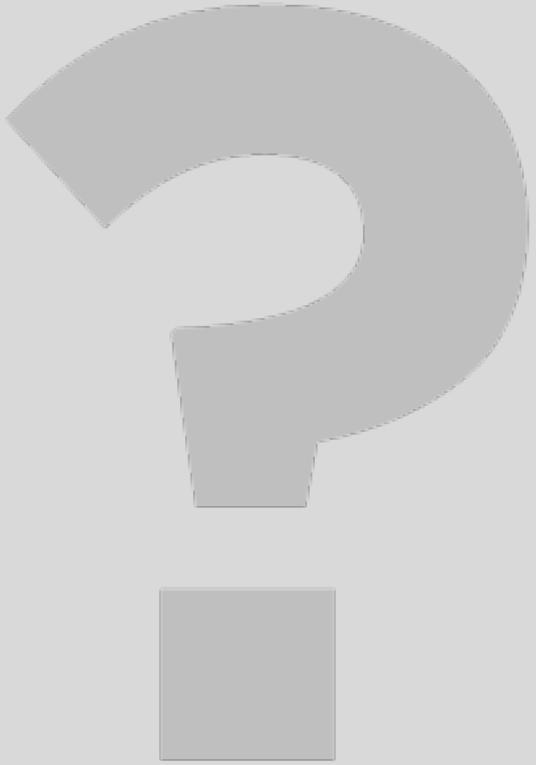

Polymers are When We Assemble Few Different Monomers Together

A. True
B. False

Knowledge Check

Polymers are When We Assemble Few Different Monomers Together

A. True
B. False

That would be an oligomer; Polymers are way more then a few monomers…

Thermoset Polymers

- The fundamental concept of thermoset polymers is that they can be subjected to one cycle after which they set (cure)
- It is not possible to reheat and cool them, they will char and their properties will degrade
- Thermoset are Thermo + set to emphasize on the curing/setting portion which influence the cross-linked molecular structure

Brittle

High range of operating temperature

Rigid

Higher resistance to solvents

TP: Recycling

- Traditional and conventional thermoset polymers are not recyclable
- The curing process influences the molecular structure in a way that renders them unable to melt/reform
- Traditionally they can be chopped and used as filler materials

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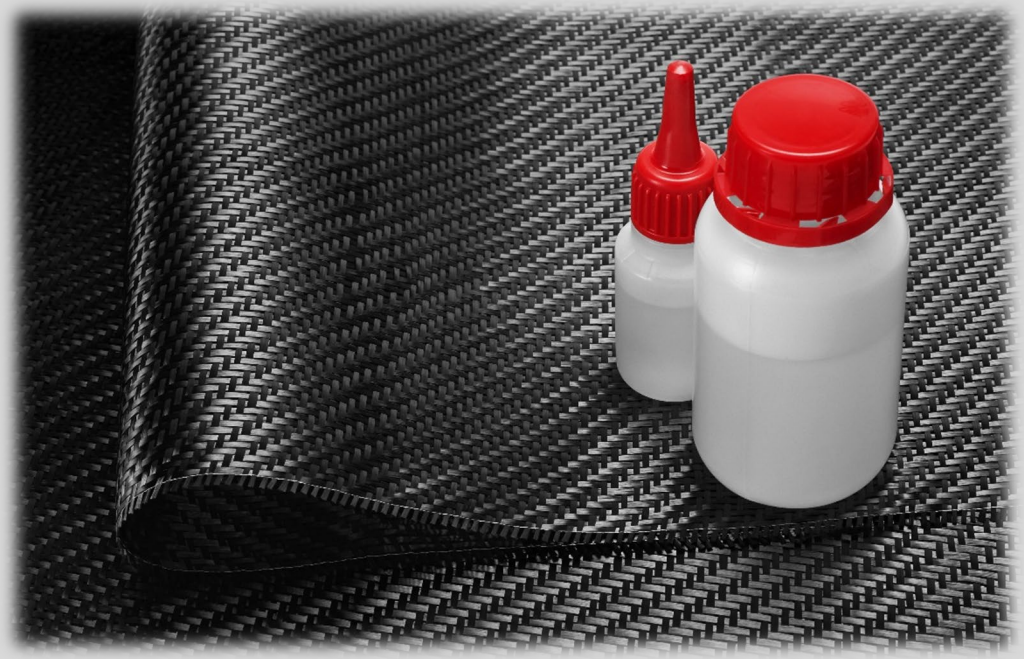
- Research on creating recyclable thermoset polymers is ongoing
- IBM proposed a new polymer that breakdown in acidic conditions | J M García et al, Science, 2014, 344, 732 (DOI: 10.1126/science.1251484)

TS: Prominent Applications

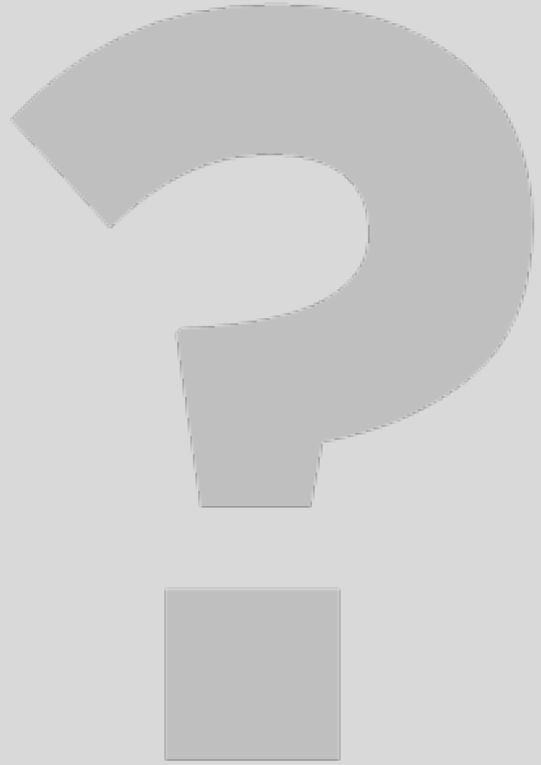
- One of the most famous application is **epoxy resins** being the matrix element in composites

Epoxy



Carbon Fiber

Knowledge Check



The fundamental concept of thermoplastic polymers is that they can be subjected to multiple heating and cooling cycles with minimal degradation

A. True
B. False

Knowledge Check

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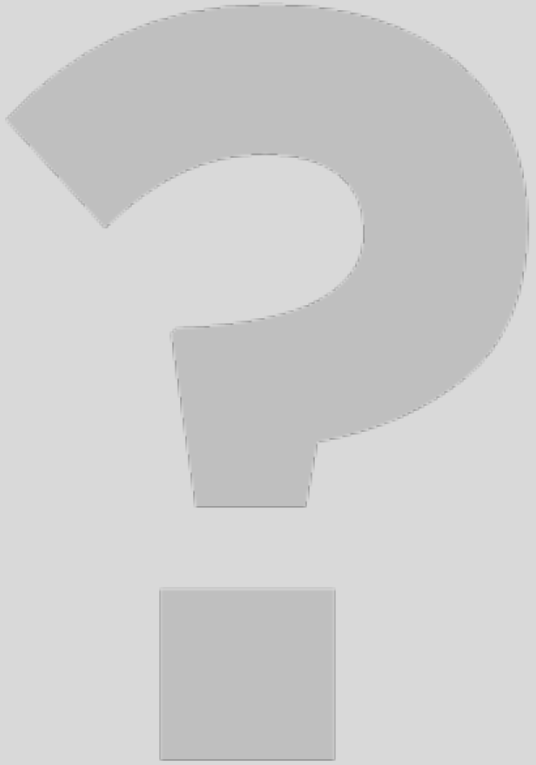
A. True
B. False

Knowledge Check



One of the most famous thermoset applications is using epoxy as the reinforcement element in composites

A. True
B. False

Knowledge Check

One of the most famous thermoset applications is using epoxy as the reinforcement element in composites

A. True
B. False

Polymers are the matrix material, carbon is the reinforcement element

Elastomers

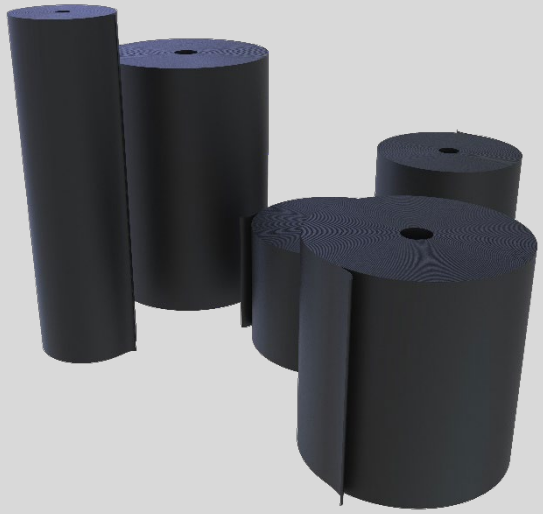
- Elastomers is derived from Elastic Polymer
- Elastomers have a loosely cross-linked molecular structure
- Elastomers are natural or synthetic
- This enables them to elongate when subjected to loads
- They are capable of recovering to their original shape once the load is removed
- Elastomers are typically thermosets, however thermoplastic elastomers also exist

Elastomers: Recycling

- Elastomers with their chemically cross-linked polymers are **not fusible and can not be reshaped**
- (Not ideal form of) recycling of elastomers is to **shred material and blend it** in a matrix with new rubber material – downside: material properties get (much) worse
- Thermoplastic Elastomers (TPE) are ‘rubber-like’ material that combines the benefits of Thermoplastics (recyclable / recyclable) with the material properties of elastomers (elastic deformation / feel)

Elastomers: Prominent Applications

- **Industrial**
  - Seals /O-rings
  - Gaskets
  - Noise reduction
  - Dampening
- **Automotive**
  - Tires
  - Windshield wipers
- **Everyday life**
  - Rubber ducks
  - Bumpers



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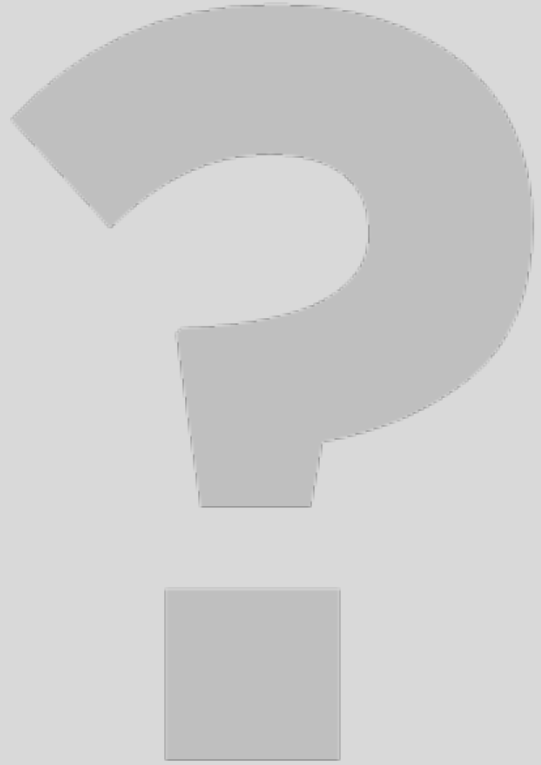


Elastomers Have a High Young's Modulus

A. True
B. False

Knowledge Check

Elastomers Have a High Young's Modulus

A. True
B. False

On the contrary, Elastomers have a low young modulus.

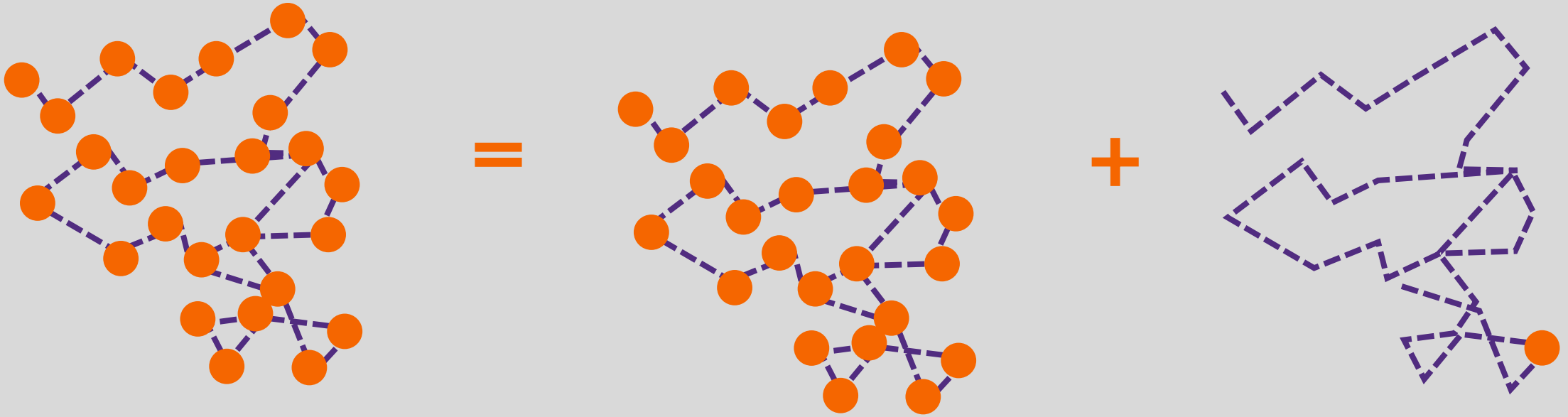
Polymerization

Section II

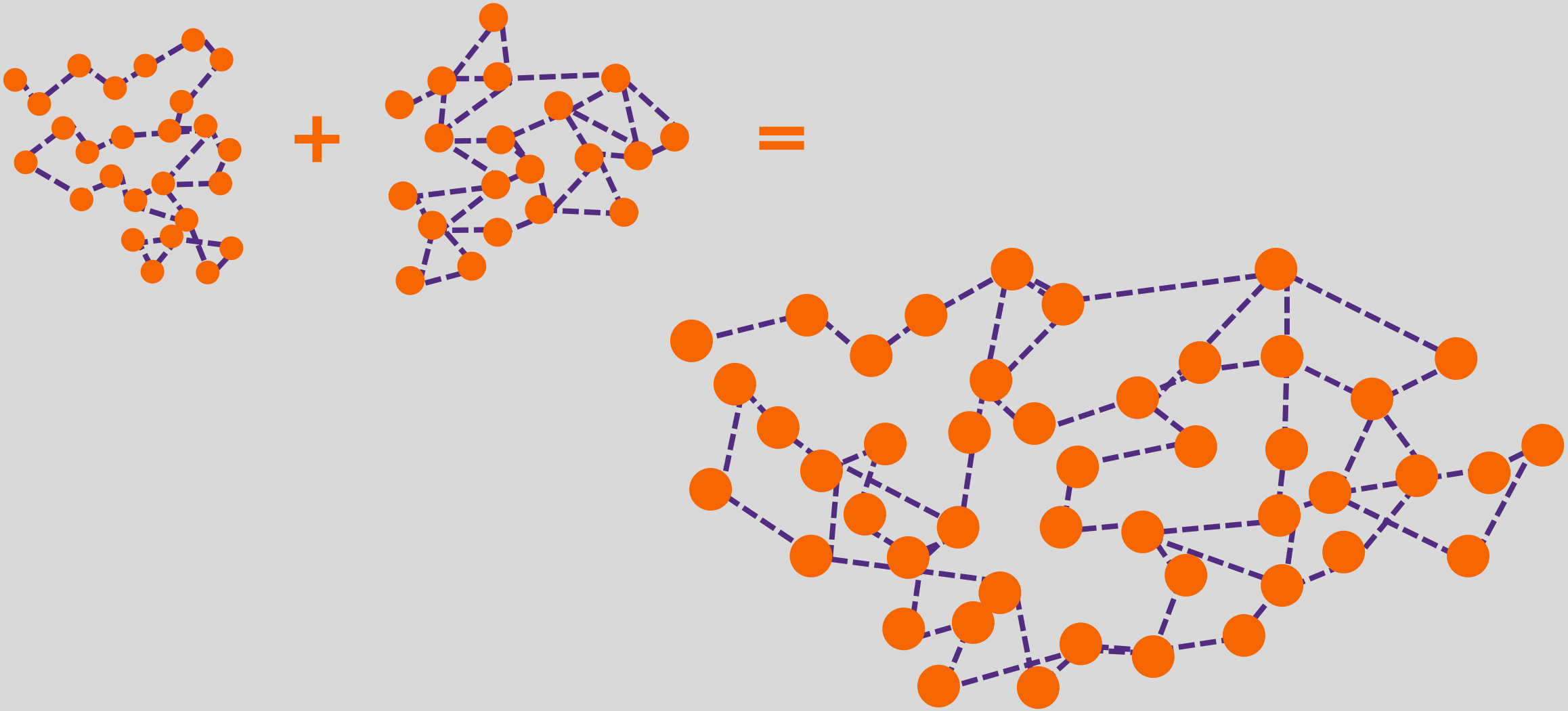
Polymerization

- The process of creating a polymer from monomers
- Polymers can be obtained through addition polymerization (Chain Growth) or step polymerization (Step Growth)
- Polymerization have an effect on the final polymer and its degree (number of polymers that were added or combined) constitutes the degree of polymerization
- Some polymers are created in a way to have components that are still inactive and as such they transform based on certain conditions from one type to another
- An example is temperature activated where a thermoplastic becomes a thermoset

Polymerization: Addition



Polymerization: Step



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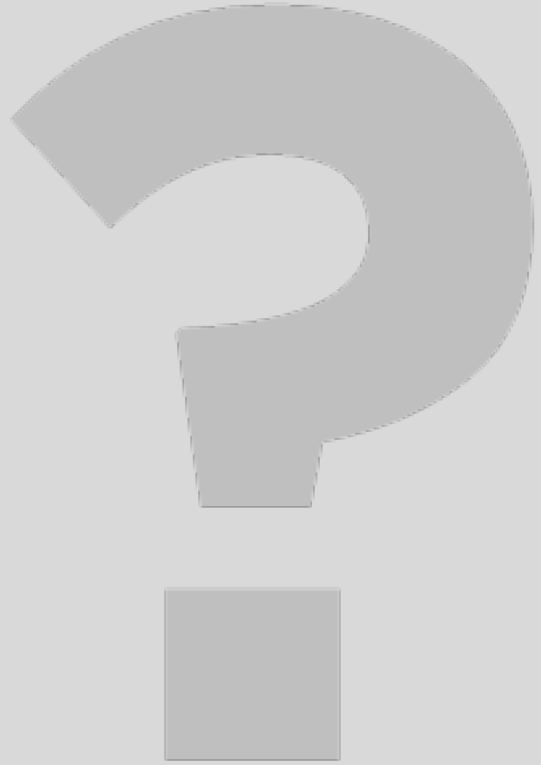


What are the Polymerization Methods?

A. Multiplication
B. Step
C. Addition
D. Subtraction
E. Both B & C

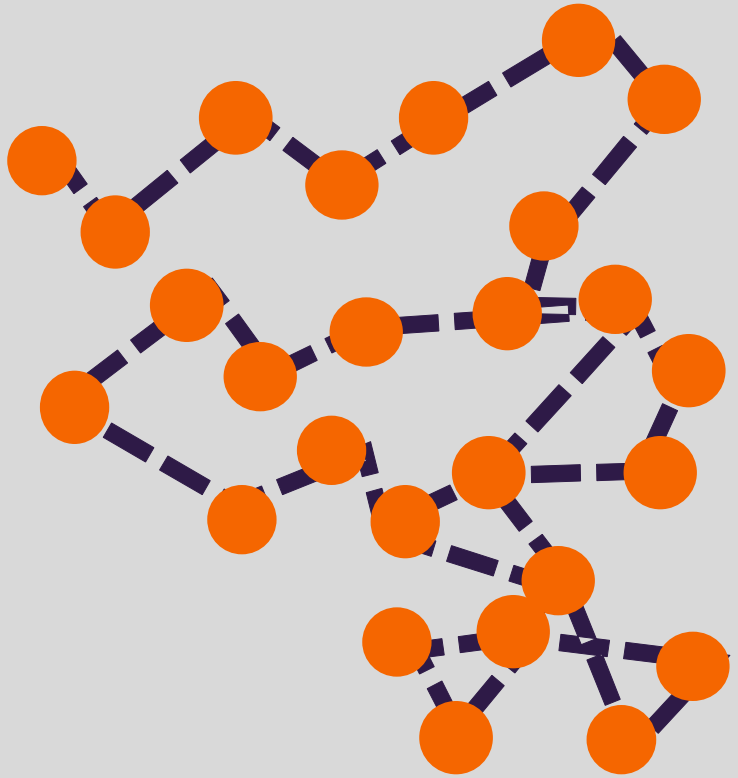
Knowledge Check

What are the Polymerization Methods?

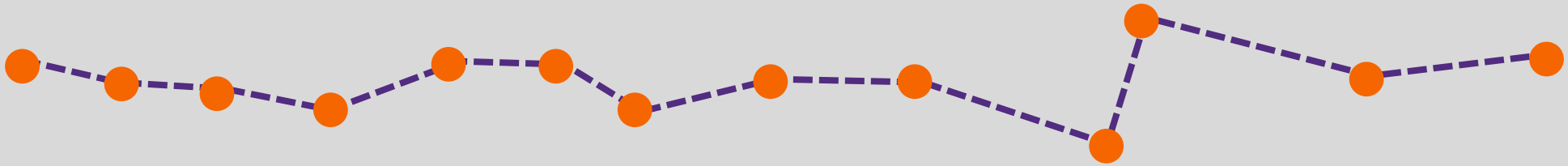
A. Multiplication
B. Step
C. Addition
D. Subtraction
E. **Both B & C**

Molecular Structure

- Polymerization methods results in a macro molecular structure of the polymer
- This chemical process that assembles monomers has a major effect:
- The simpler the structure the easier to reshape and recycle
- The more complex the structure the harder to reshape and recycle
- The molecular structure inherently explains the type of polymer that is obtained
- Simple structures are thermoplastic polymers
- Complex structure are thermoset polymers

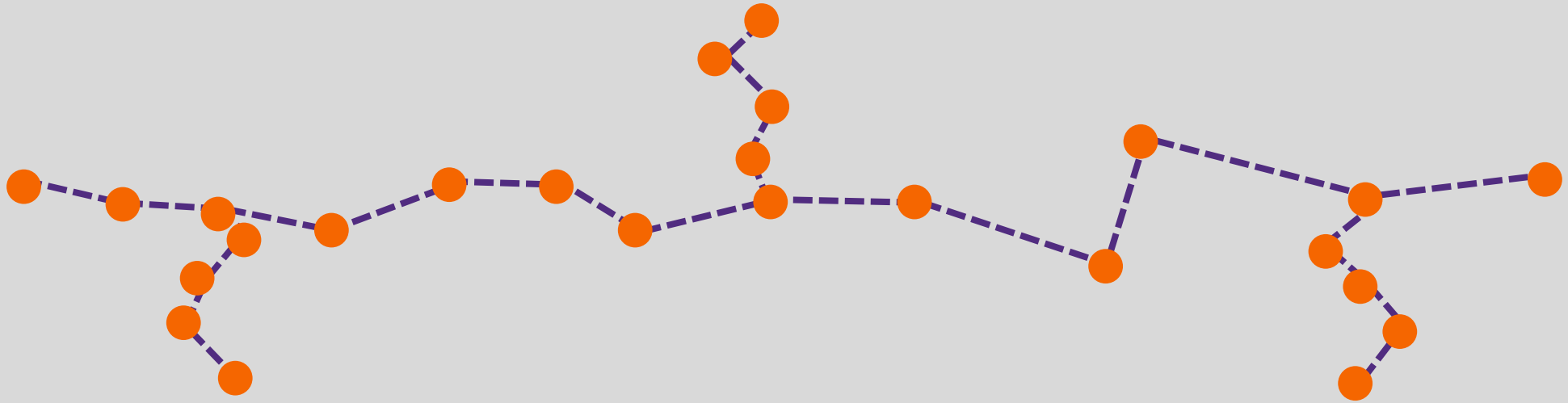


Molecular Structure: Linear



- Typical of thermoplastic polymers
- The linear structure provides fluidity for reheat/remelting and as such enables the recycling of thermoplastics

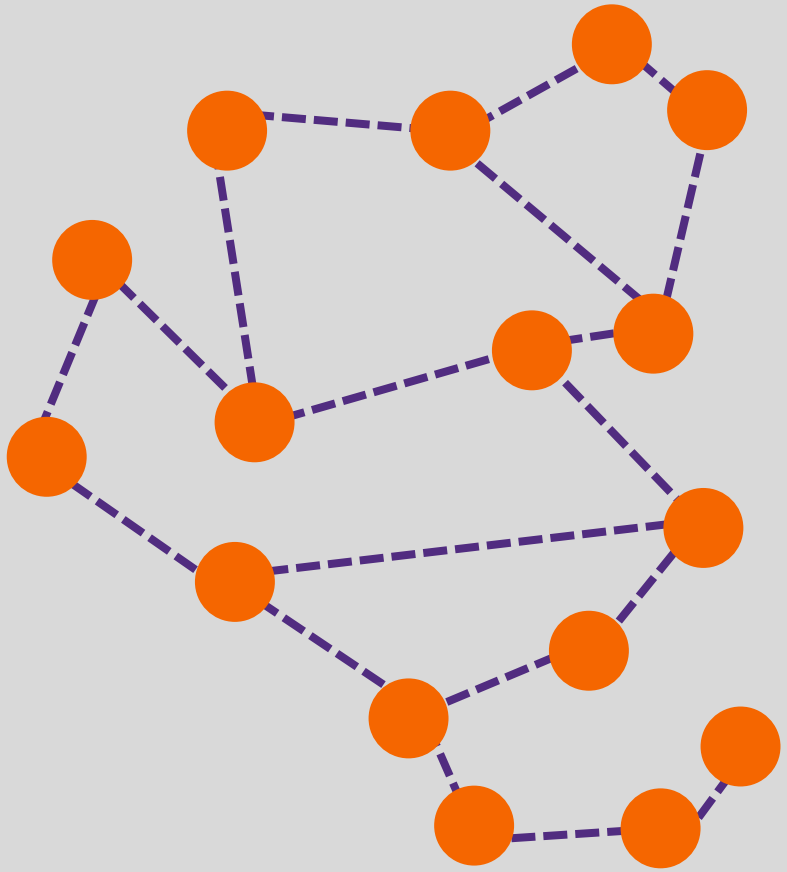
Molecular Structure: Branched



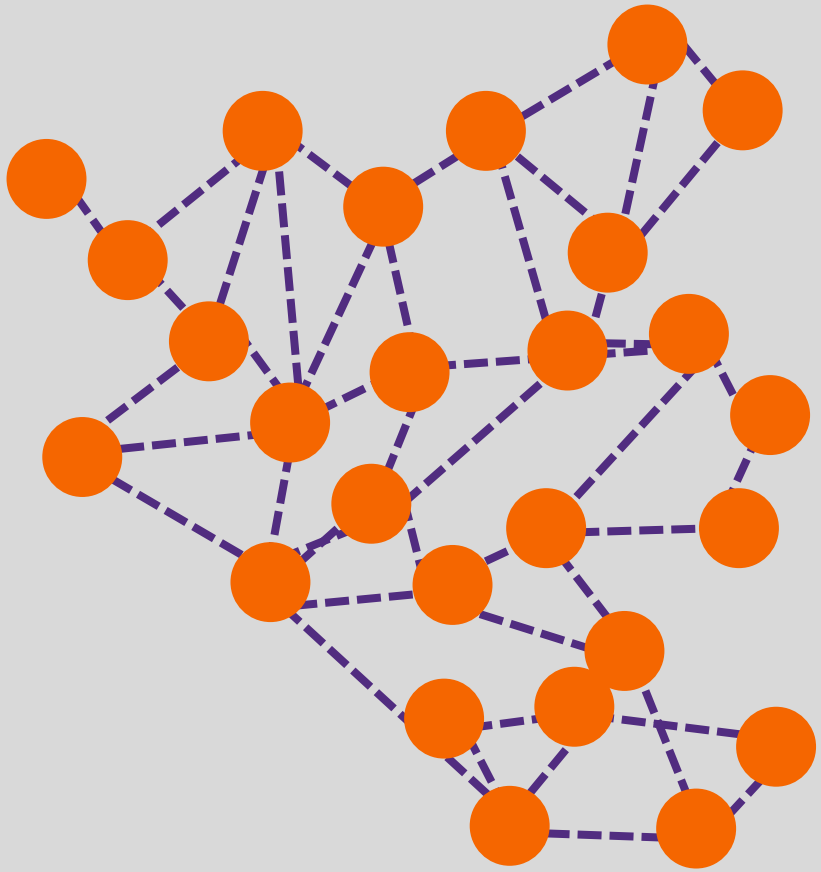
- Typical of thermoplastic polymers
- Similar to the linear structure and as such it enables recycling

Molecular Structure: Cross-Linked

Loosely cross linked

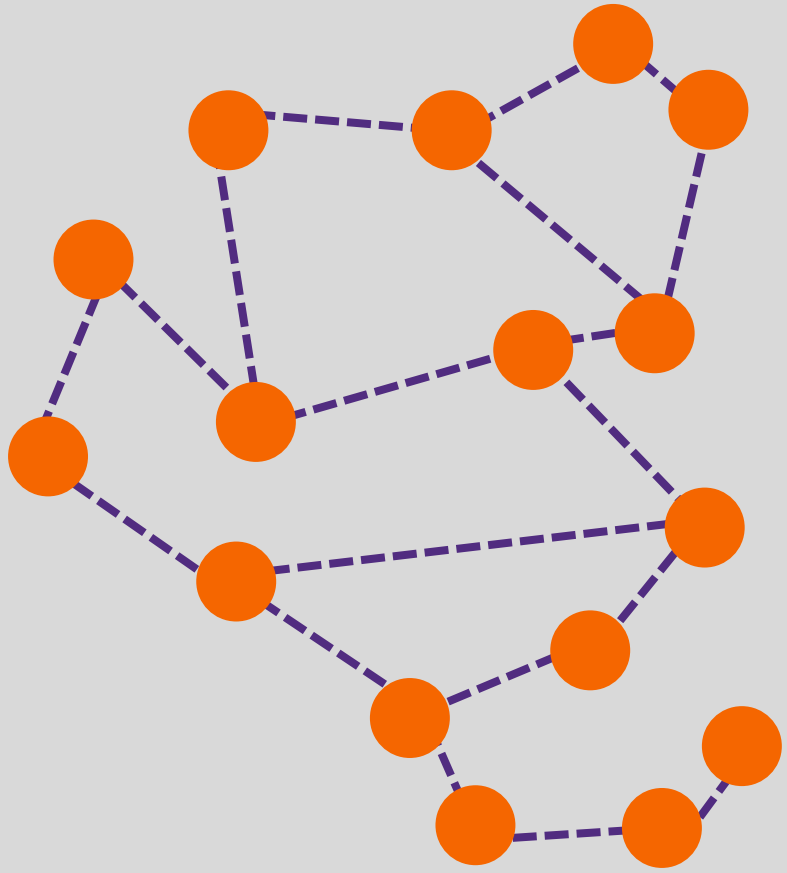


Tightly cross linked



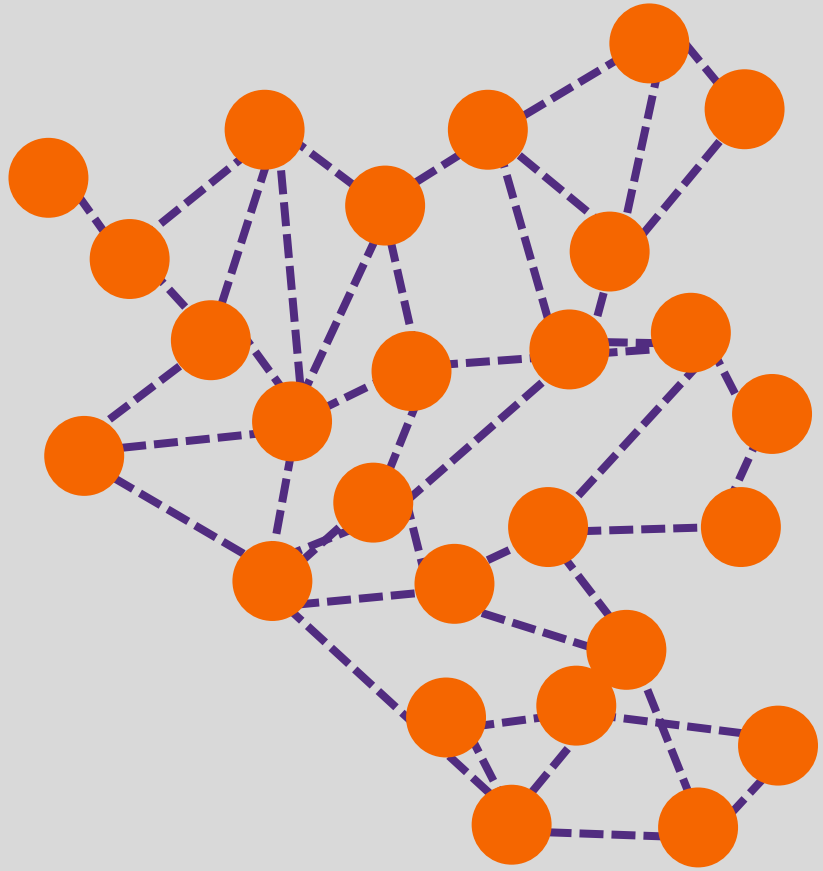
Molecular Structure: Loosely Cross-Linked

- Typical of Elastomers
- It enables elongation and will return to initial shape after load is removed
- Can include temperature-activated components to become tightly cross-linked



Molecular Structure: Tightly Cross-Linked

- Typical of Thermosets
- Is highly cross linked and as such not suitable for recycling nor reshaping



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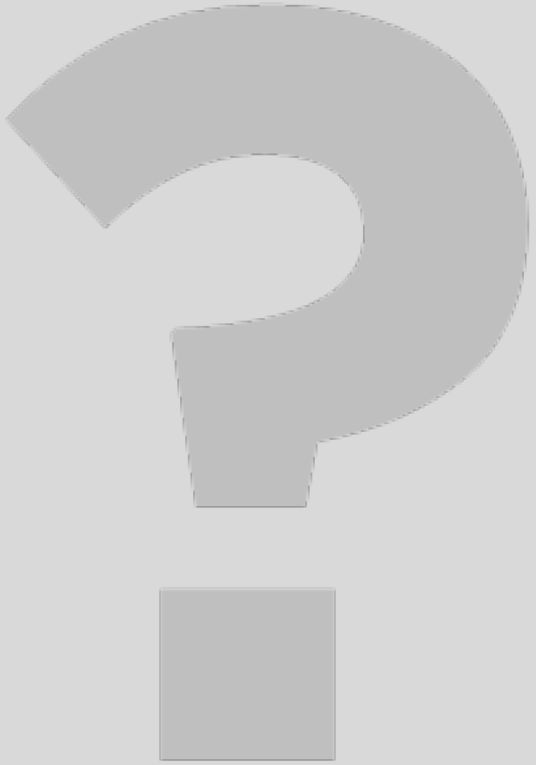


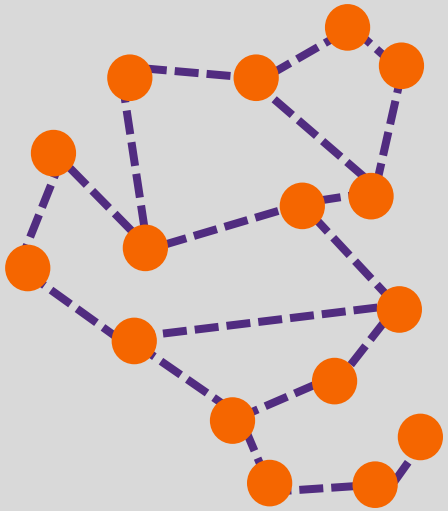
Which Molecular Structure is Most Likely to be an Elastomer?

A. Linear
B. Branched
C. Loosely cross-linked
D. Tightly cross-linked
E. None of the above

Knowledge Check

Which Molecular Structure is Most Likely to be an Elastomer?

A. Linear
B. Branched
C. **Loosely cross-linked**
D. Tightly cross-linked
E. None of the above



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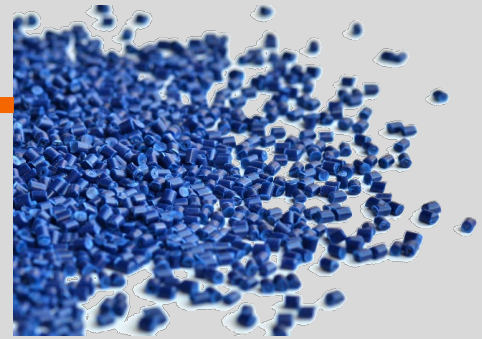
Injection Molding

Section III

Process Concept

2

1



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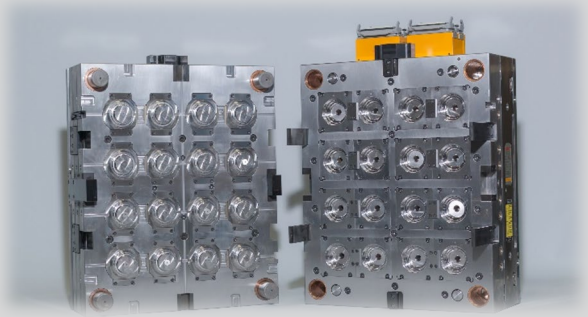


4

Process Concept

- **Preparation**
  - Mixing of plastic raw material(s) with other materials required for process (e.g., colorant)
- **Screw**
  - Selection crucial for quality
  - Various designs (e.g., pitch, flight depth, etc.)
  - Material and process dependent
- **Three-section screw**
  - Works with wide variation of materials
  - 1 Sec: Feed section (~50-55% length of screw)
  - 2 Sec: Compression section (~25-30%)
  - 3 Sec: Metering section (~20%)
- **Ejection**
  - Ejection pin marks can be found on most injection molded plastic parts

Generalized injection molding process:

Preparation of raw materials
- Drying plastic pellets
- Sizing of plastic pellets
- Mixing of plastic pellets

Melting and mixing of material
- Mixing: screw rotational movement
- Heating: a) outer heating bands &
- b) compression/friction of screw

Injection of material
- Injection through axial movement of screw (e.g., hydraulic ram)
- Check ring of screw acts as 'seal'
- Mold cavity filled w/ high pressure

Cooling of material
- (Most) shrinkage occurs in mold
- New: Additive Manu. allows built-in cooling channels

(Automatic) ejection of parts
- Opening of mold
- (Auto.) ejection using ejection pins

Application

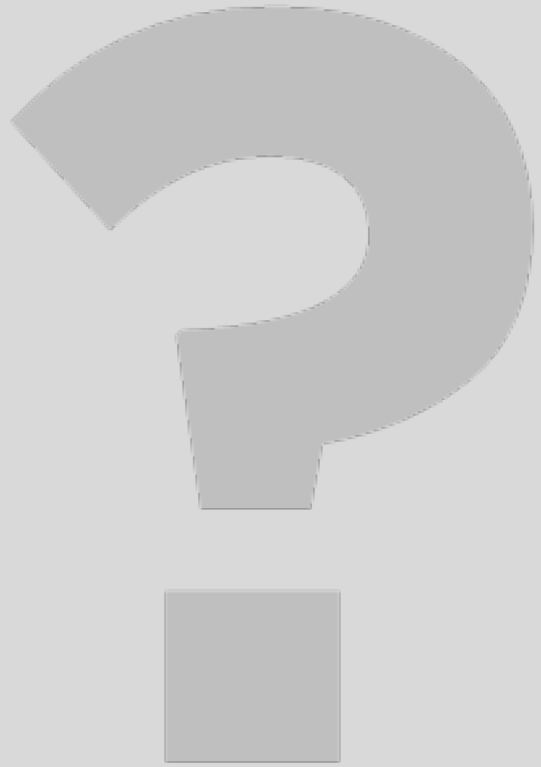
- Wide variation of applications
- Many items of daily use
  - Plastic forks/knives
  - Combs
  - Cups
- Toys
  - Lego
  - Toy cars
- Industrial use
  - Automotive: Dashboards, interior trim, bumpers, etc.
  - Aerospace: Lenses, panels, containers, bezels, etc.
  - Medical: Parts for thermometers, heart pumps, etc.
  - Etc.

Advantages and Disadvantages

- Advantages
  - Highly automated process
  - High throughput (fast production)
  - Capable of producing detailed features
  - Capable of producing complex geometry
  - Very efficient (given large batch size)
  - Ability to enhance material strength using fillers
  - Ability to create multi-material parts in one mold
  - No to little post-processing required
  - Reduced waste/scrap
- Disadvantages
  - (Very) high tooling cost (mainly molds; partly special screws)
  - There are certain restrictions regarding part designs (e.g., taper/draft angle, wall thickness, Radii, undercuts, etc.)
  - Only economically feasible for larger batch sizes


For more check:
introtomanufacturing.com

Knowledge Check



What function has the screw in an injection molding system?

A. Moving the plastic raw material(s)
B. Mix the plastic raw material(s)
C. Heat the plastic raw materials
D. All of the above

Knowledge Check

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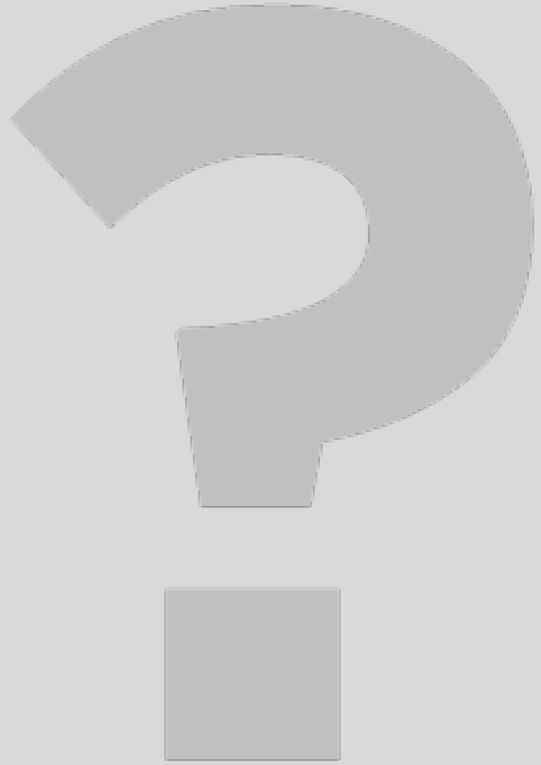


Polymer injection molding might be the right manufacturing process when…

A. A large number of similar products should be produced
B. A small batch products with a complex geometry should be produced
C. A large number of identical products with a complex geometry should be produced
D. None of the above

Knowledge Check

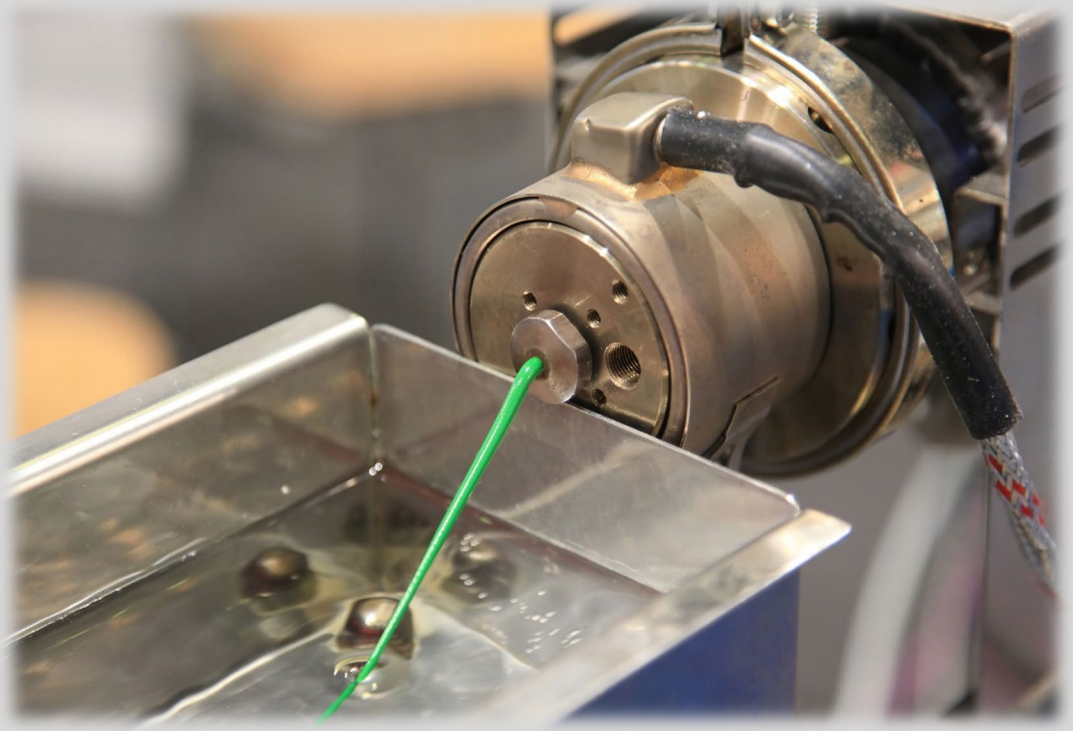
Polymer injection molding might be the right manufacturing process when…

A. A large number of similar products should be produced
B. A small batch products with a complex geometry should be produced
C. **A large number of identical products with a complex geometry should be produced**
D. None of the above

Extrusion Molding

Section IV

Process Concept



Process Concept

- **Materials**
  - Different material grades required than for other polymer manufacturing processes
- **Shapes**
  - Most constant cross-section profiles can be manufactured (e.g., U-/O-/T-/H-shape, square)
  - Very thin films (<0.02in) and sheets (<0.5in) can be produced
  - Theoretically the process can produce a 'endless' part
- **Cooling / Cutting**
  - After extrusion, material is normally transported on a belt system
  - It is automatically cooled and either cut to desired length (rigid or flexible material) or coiled (if continuous, flexible material)

Generalized extrusion molding process:

Preparation of raw materials
- Drying plastic pellets
- Sizing of plastic pellets
- Mixing of plastic pellets

Melting and mixing of material
- Mixing/transport screw rotation
- Heating through heaters at nozzle (some system also screw friction)
- Pressure build up for extrusion

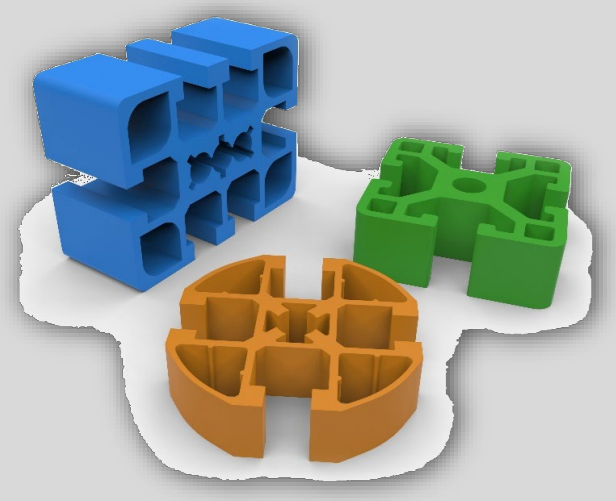
Extrusion of material
- Extruded through constant cross-section profiles
- Possibility to produce sheets/films
- Mold cavity filled w/ high pressure

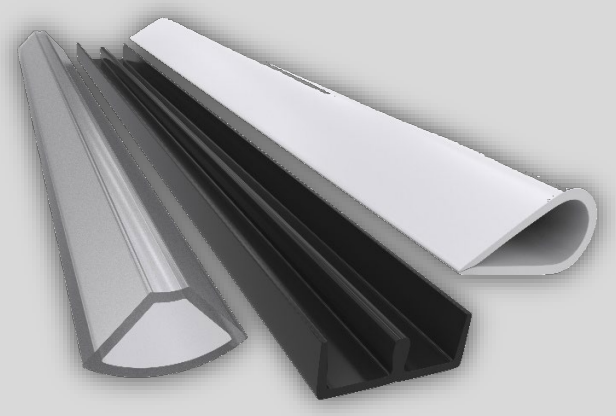
Cooling of material
- Continuous cooling through
- a) air or
- b) water (spray/bath)

Cutting or coiling
- Cut to length (profiles)
- Coiled (for continuous materials)

Application

- A wide variety of constant cross section products and parts
- Some examples:
  - plastic tubing,
  - insulation for wires,
  - pipes,
  - rods,
  - rails,
  - seals,
  - T-/L-/H-profiles,
  - sheets,
  - Films
  - etc.





Advantages and Disadvantages

- Advantages
  - Comparably low tooling cost
  - Ability to produce continuous parts (theoretically endless)
  - Very high production volume (high throughput)
  - Low cost of parts
  - Efficient process
  - Little to no waste/scrap
  - Production of multi-material products possible
  - Easy post-process manipulation (part comes out hot which allows certain alterations)
- Disadvantages
  - Limited complexity of parts
  - Limited to parts with constant cross-section
  - Limited material selection (compared to injection molding)

For more check:

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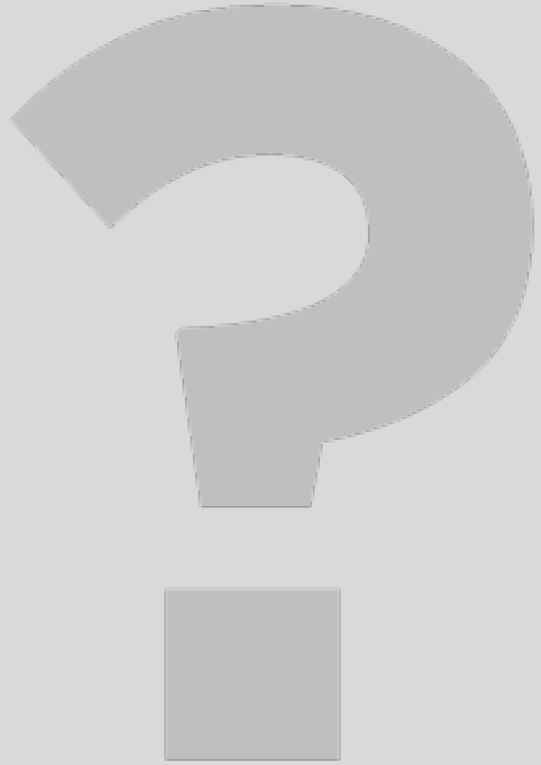
Knowledge Check



The polymer extrusion process can produce multi-material products

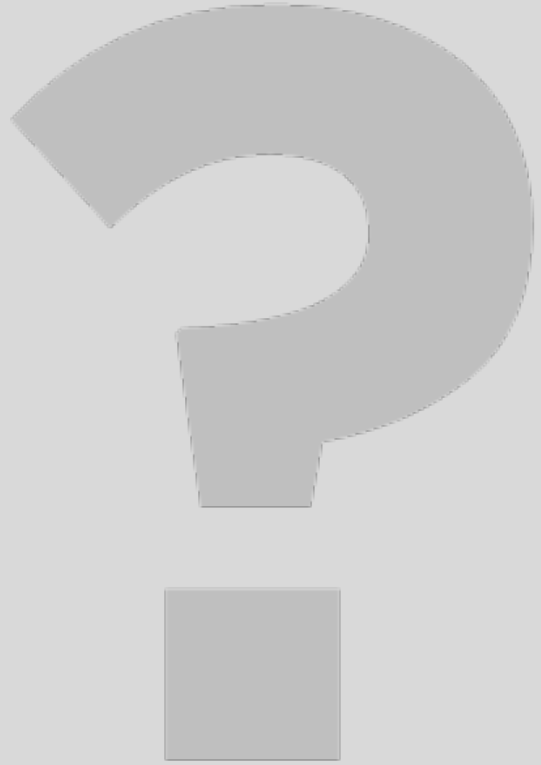
A. True
B. False

Knowledge Check

The polymer extrusion process can produce multi-material products

A. True
B. False

Knowledge Check



All the same raw material can be used for polymer injection molding and extrusion process

A. True
B. False

Knowledge Check

All the same raw material can be used for polymer injection molding and extrusion process

A. True
B. False

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Blow Molding

Section V

Process Concept

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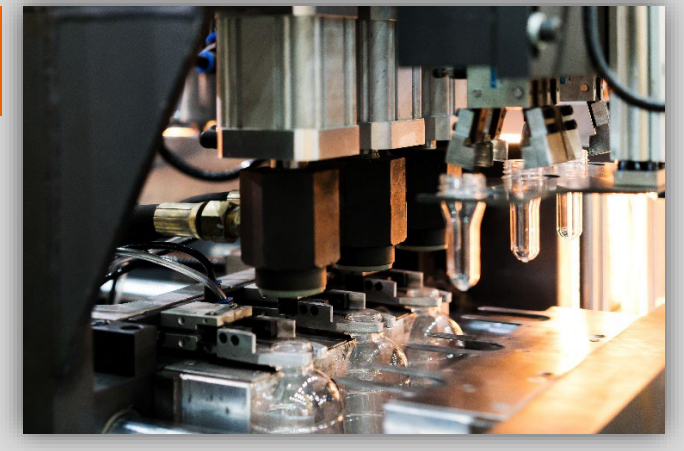

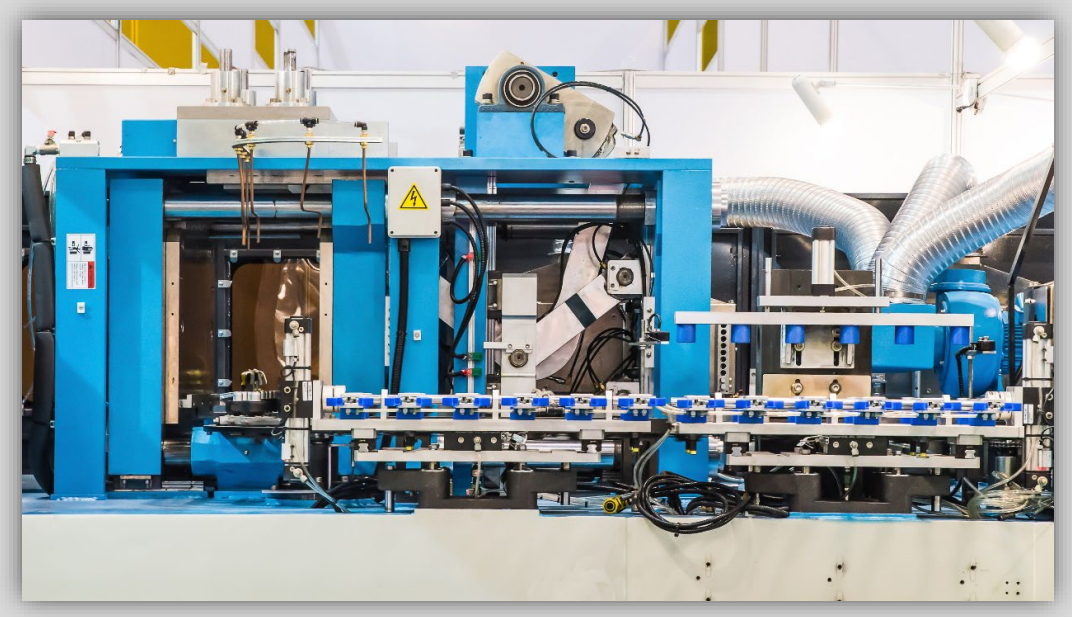

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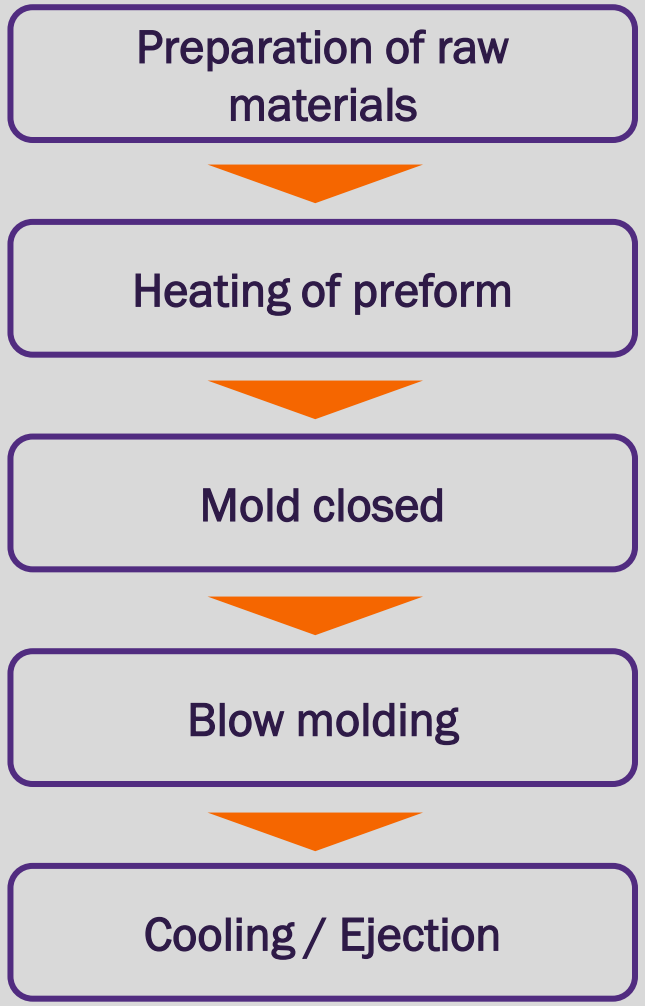
Process Concept

- Materials
  - Solid-bottom, hollow preform (mainly injection molded)
  - There are variations where ‘preform’ is produced directly in the same process:
    - Injection blow molding (using 2 different molds – preform/final-form)
    - Extrusion blow molding (Mold/blow pin seal open ends)
- Shapes
  - Produces mainly seamless, hollow shaped containers (e.g., plastic bottles, car gas tanks)
  - Achieves very good dimensional tolerances
  - Easily removed from molds (compared to injection molding)
- Variations
  - Process available that allow both axial and radial expansion of preform
  - Multilayered products are possible

Generalized blow molding process:



- Production of preform using either injection or extrusion molding process
- Preform is heated to required temperature
- Preform installed on blow pin
- Heated preform placed between two sides of open mold
- Mold closes around preform
- Air pressure burst expands the preform against sides of mold cavity

Application

- Everyday items
  - Water bottles
  - Gardening equipment
  - Household items
  - Containers of all sort
- Industrial applications
  - Containers (e.g., biohazard)
  - Plastic wheels
- Misc
  - Stadium seats
  - Parts of hospital beds
  - Coolers

Advantages and Disadvantages

- Advantages
  - Comparably low mold cost (compared to injection molding) & system cost
  - Possibility to mold (relatively) complex geometries (e.g., external threads)
  - High production cycle / volume
  - Automation level
  - Ability to make hollow parts
  - One-piece (seamless) products
  - Multi-layer products possible
  - Excellent pressure performance of final parts
- Disadvantages
  - Limited features (e.g., no holes, other than opening for blow pin, can be molded in)
  - Wall thickness limited
  - Limited to hollow containers of some sort
  - Limitations on diameter of parts (to uphold tolerances in, e.g., corners)
  - Comparably high amount of scarp parts (compared to extrusion/injection molding)
  - (impact of products on environment)

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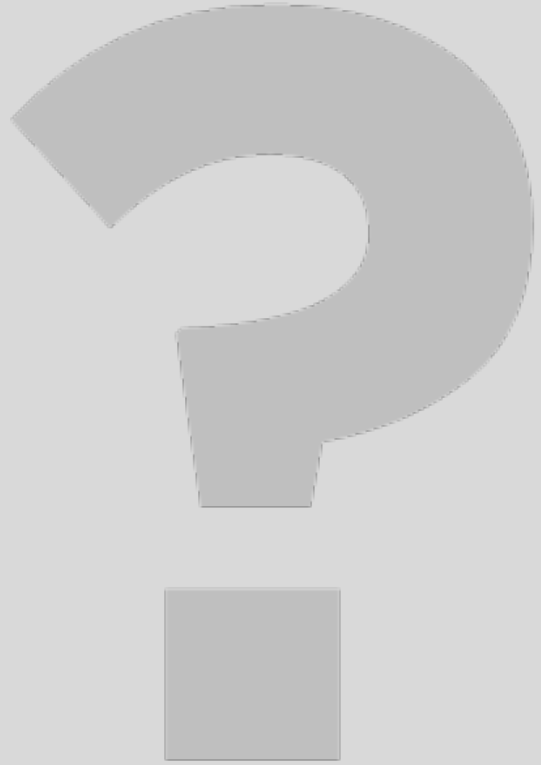
Knowledge Check



The polymer blow molding process can not produce

A. Parts with holes
B. Parts with multiple layers
C. Parts with complex geometries
D. Hollow parts
E. None of the above

Knowledge Check

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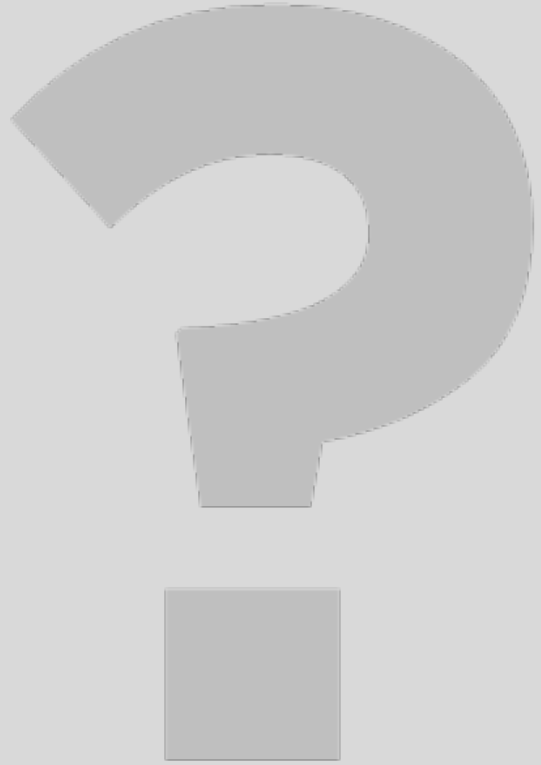

The polymer blow molding process is often combined with other polymer manufacturing processes

A. True
B. False

Knowledge Check

The polymer blow molding process is often combined with other polymer manufacturing processes

A. True
B. False

THANK YOU

- This set of slides is retrieved from the textbook: Intro to Advanced Manufacturing, Harik/Wuest, ISBN 978-0-7680-9327-8 978-0-7680-9327-8
- Link of the textbook: https://www.sae.org/publications/books/content/r-463/
- For more information:

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