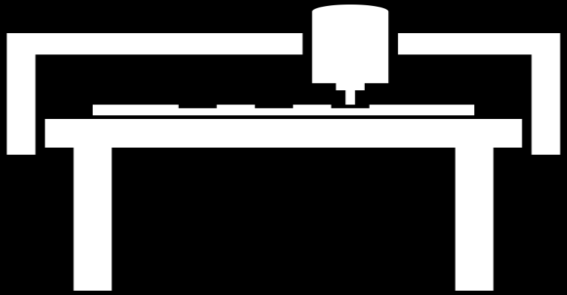
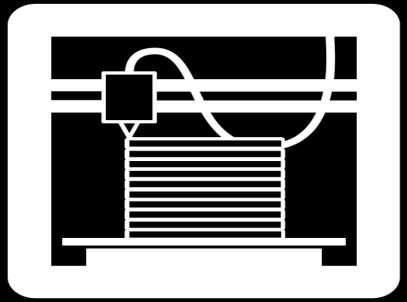
Manufacturing Processes

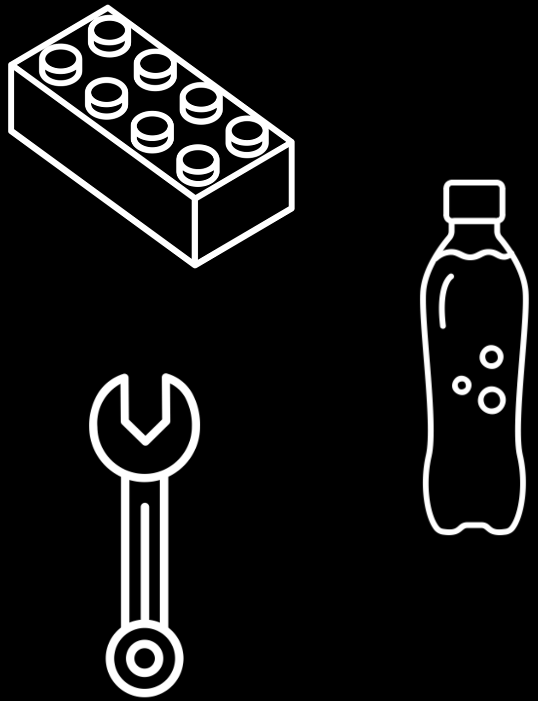




Manufacturing Processes refer to the machinery, labor, and materials needed to make products in multiples.

- Take note of the common themes that arise: material choices, geometry constraints, mold costs, output volumes, and labor costs.

- Lastly, being able to understand how the products you use everyday are manufactured can ultimately help you become a more thoughtful, sustainable, and efficient product designer.



Additive technologies refer to raw material being inputted in one form and then casted or “added” together to form an object.

Subtractive technologies refer to an input of a larger block of material that is then cut away/subtracted from to form an object.

Forming (or Net Forming) refers to objects that are made through manipulation of an input material through cutting, bending, and other manipulation techniques.

Additive

- Injection Molding
- Die Casting
- Sandcasting
- Extrusion
- 3D Printing

Subtractive

- Milling/CNC
- Turning

Deformative

- Vacuum Forming
- Blow Molding
- Stamping

Injection Molding

- One of the most common processes
- Make plastic parts quickly, cheaply, and at large volumes.
- **Input:** thermoplastic pellets (a plastic that can be re-melted several times without changing its properties)
- The plastic pellets are then heated to a tooth-paste like consistency and injected into a metal mold in the shape of the object.
- Parts are ejected from the mold and the process starts all over again.

Injection Molding: Materials

Several different types of plastics can be used in injection molding, but some of the most common are:

- **ABS (acrylonitrile butadiene styrene)** is tough, cheap, and easily moldable but not very easily recyclable
- **PE (polyethylene)** comes in 3 varieties PETE (polyethylene terathalene, HDPE (high-density polyethylene), and LDPE (low-density polyethylene). It is fairly ductile and recyclable.
- **Silicones and Elastomers** (flexible parts)

Injection Molding: Pricing

- **High cost: the mold itself**
  - Molds typically cost $5k-$50k, and can produce millions of parts.
  - Size, complexity, and domestic or int’l manufacturing are factors of cost. More complex molds are more expensive.

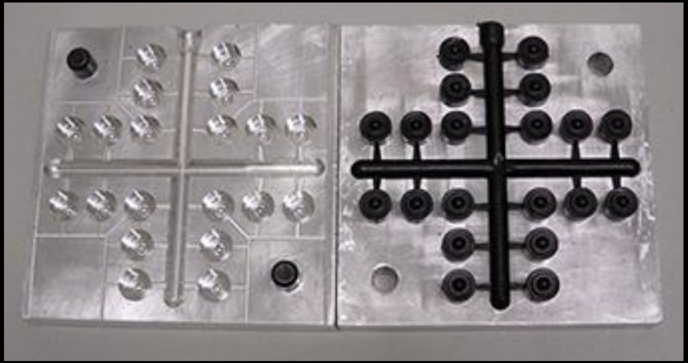
- **High cost: accuracy of the mold**
  - Also to create a smooth or shiny surface finish usually entails someone manually polishing the cavities of a mold by hand. A shiny mold surface = a shiny plastic part.

- **Low cost: individual part**
  - Less than a penny (for something like a bottle cap or a syringe) to ~$10 (for something like a plastic chair).

- Because of this pricing scheme, it only makes sense to use injection molding if you will produce thousands, or even millions of parts in order to recoup your high cost of the mold production.

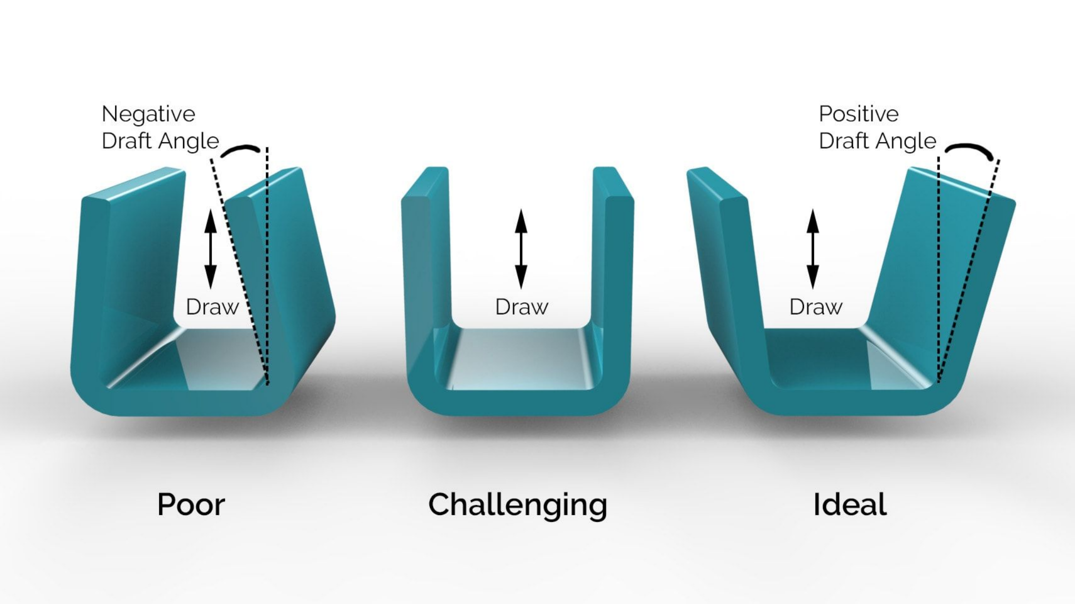
- One cost-saving technique is to create a multi-cavity mold that produces 4-8 parts at a time

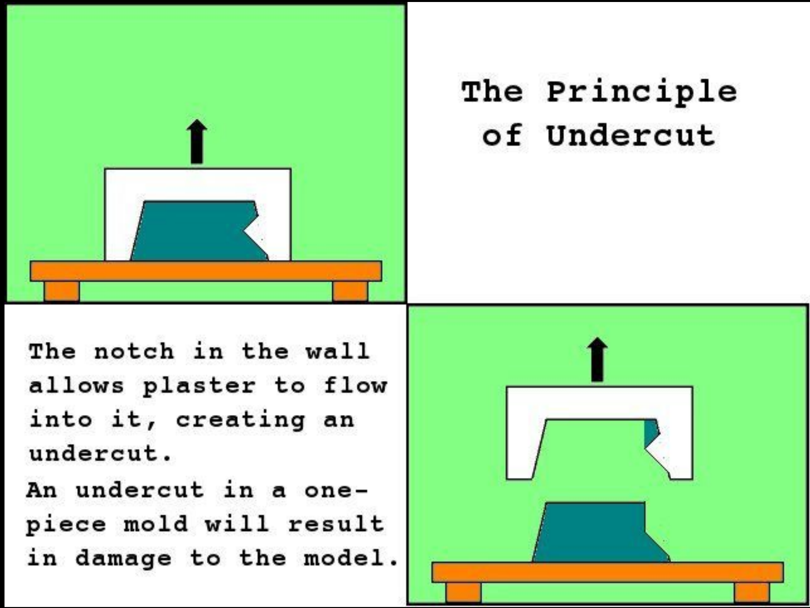
An Injection Mold being polished.



A multi-cavity injection mold

Injection Molding: Constraints

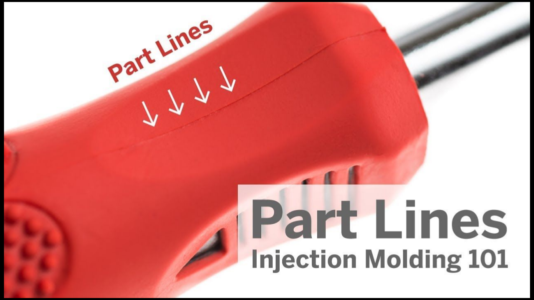


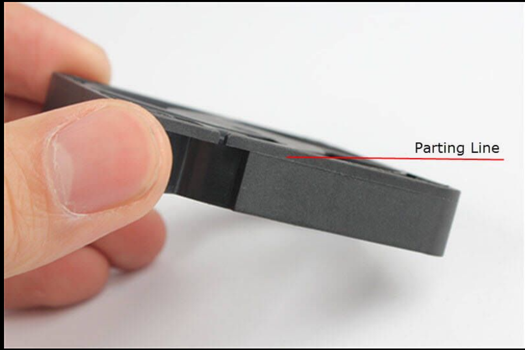


Draft is important in making sure your object can be ejected from the mold. Draft refers to the angle of walls in relation to the direction of the mold opening and closing (known as the direction of the Draw). The object needs to be able to pop out easily.

Undercuts are also features of your objects that would preclude it from coming out of the mold. A more complex object tends to have more undercuts, and can take a more complex (and more expensive) mold design to achieve the production of a part.

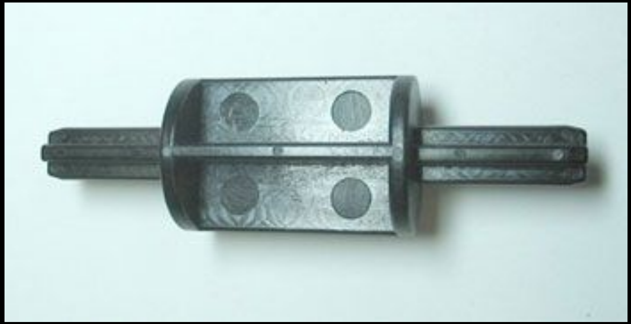
Injection Molding: how to identify?

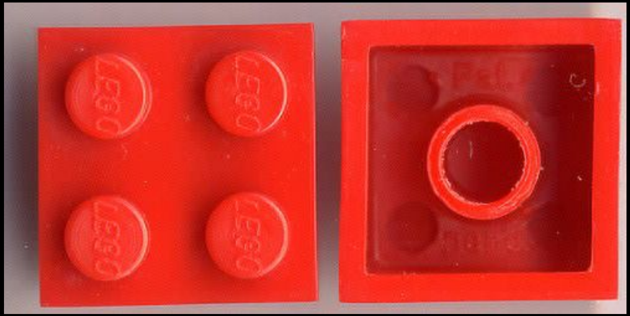




One of the most obvious identifiers of the injection molding process is simply the object being made out of plastic or silicone.

***Parting Lines* are an artifact leftover from the casting process and manifest as a line of raised material on an object**. Where two halves of a mold meet, a little bit of plastic material can squeeze out between the space between.





***Ejector Pin Marks* are small, circular indentations on the underside of a plastic part.** These artifacts are made from an ejector pin, a moving part of a mold responsible for pushing a finished part out of the mold.

Die Casting

- **Die Casting is functionally identical to injection molding, except that the input is molten metal rather than plastic or silicone.**

- Similarly a steel mold has to be made, which can cost more than a plastic injection mold since very strong alloys of steel need to be used.

Die Casting: Materials

- **This process most commonly used the metals aluminum, magnesium, and zinc.**
  - These metals are softer (with lower melting temperatures) and more easily castable than steel which makes them good candidates for the die casting process.

- These metals are generally lightweight in comparison to steel, but are still strong and durable

- Components for bikes, scooters, and skateboards, kitchen utensils, etc.

Die Casting: Materials

Zinc, Magnesium, and Aluminum are metals that are both light in color *and* light in weight and can be die cast.

By contrast, steel is heavy in weight and dark in color (can't be die cast)

Die Casting: Pricing

- **The pricing scheme for die casting is similar to injection molding.**
  - However, a higher strength steel often needs to be used in die casting that can raise the mold price to $10k-$100k (some cost more than $500k) and can produce 100,000 to 1 million parts.

- **The individual cost per part is low** ranging from less than a dollar for something small, to $10's of dollars for something larger like a scooter deck.

- Because of this pricing scheme, it only makes sense to use die casting if you are intending to produce tens of thousands to even millions of parts in order to recoup your high cost of the mold production.

Die Casting: Pricing

A mold costing approximately $44,000 used to make magnesium scooter decks.

Die Casting: Constraints

- **Undercuts and draft angle (just like with injection molding)**
- **Labor to post-process**
- Volume of objects you intend to produce. Die casting is best for large quantities due to high startup cost.
- Use of multi-cavity molds to produce small parts at cheaper cost

Die Casting: how to identify?

Parting Lines can also be seen on die cast parts. Often they are grinded away in post-processing.

One of the most obvious identifiers of the die casting process is simply the object being made out a lightweight and light in color metal (that isn't steel).

Circular ejector pin marks.

Sand Casting

- **Sand Casting is a process commonly used to cast ferrous metal (steel and iron) using packed sand as the mold material.** The sand includes an additive so it can be packed together and hold it's shape, similar to a snowball.

- The sand is packed around models of the object intended to be casted; these models are called *patterns*

- Molten metal is then poured into the cavity. Once it's cooled the sand mold is destroyed to remove the object.

Sand Casting: Materials

- **Sand casting is a process that is optimized to cast steel.** Steel is a more difficult metal to cast because of its high viscosity and melting temperature, making it hard to inject under pressure in a die casting process.
- However, some products call for the higher strength and resilience of steel vs. the softer metal typically used in die casting.
- High stress parts: wrenches, pipe fittings, and car disc brakes

Sand Casting: Materials

Steel and iron are heavier metals that
are dark gray to black in color

Sand Casting: Pricing

- **Sand casting is a less automated - the mold has to be remade for each casting.**
  - This increases labor cost per part, which can range in a couple of dollars to tens of dollars of cost.

- **Additionally the start up costs for sand casting are not as expensive as injection molds.** It can range from $1k-$10k to create patterns of your objects and set up a casting operation.

A lot of human labor is required in this process, adding to more cost per part.

Sand Casting: Constraints

- **Steel has a high viscosity when casted.** Hence it is not ideal for creating objects with detailed, complex geometry.

- The nature of the sand acting as the mold in the process also makes details and undercuts difficult

- **Objects casted in sand can take on the texture of the sand itself, leaving the object with a slightly rough surface finish.**

- If the casting is intended to interface with another object, such as a pipe fitting that screws into another pipe, than often the part is post-processed through milling to perfect the part of the object that needs to interface with another object.

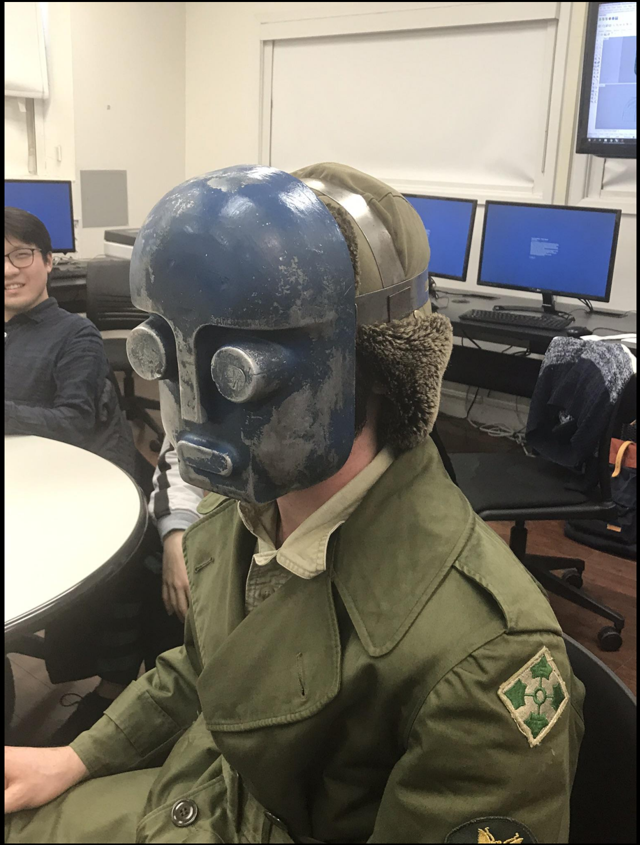
Sand Casting: how to identify

Dark gray in color and heavy in weight - as well as a small dimpled texture from the sand.

Threads are milled into the part after the casting process.

Sand Casting: DIY?

Could you? Yes. Should you? Maybe not.



One of my students' sand casted work

Extrusion

- **Extrusion is a process that creates objects with a fixed cross-section.**
- Metal, plastic, of even edible items such as pasta, are pushed through a die and then cut to a desired length to create parts or finished products.
- Though there are many design constraints when using this process, it can be very economical to design parts to utilize extrusion over a casting process.

Extrusion: Materials

- **Extruding metal is a multi-step process as you saw in the previous video, but it can produce parts with a desirable surface finish with little post processing.**
- **Most common use: PVC pipes.** Elastomers (rubbers) can also be extruded.
- **Foods made through extrusion**: pasta, cereal, granola bars, fig newtons, Cheetos!

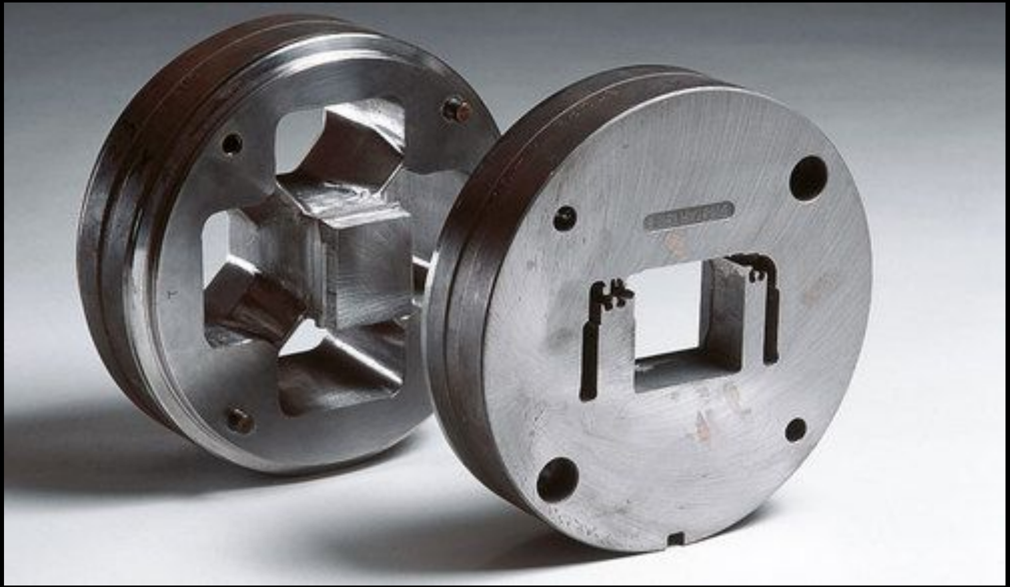
Metal extrusion can produce nice surface quality with little post processing.

My favorite extruded product.

Extrusion: Pricing

- **The main cost: creation of a die** (the “stencil” that dictates the shape of your extrusion.)
- Aluminum dies cost between $1k-$4k, and steel dies cost $5k -$20k.
- Some cost to cut the extrusions to the desired length (usually pretty automated)

Extrusion: Pricing



Steel extrusion dies.

Perhaps your first extruder.

Extrusion: Constraints

- **The main trade off when utilizing this process is the limitation of your geometry;** it must have a common cross section and two faces of your design will be flat and featureless.
- Because of the lower fixed costs, it makes economic sense to use extrusion is you are planning to produce hundreds or thousands of parts.

Brackets that were made by extrusion with holes added in a secondary process.

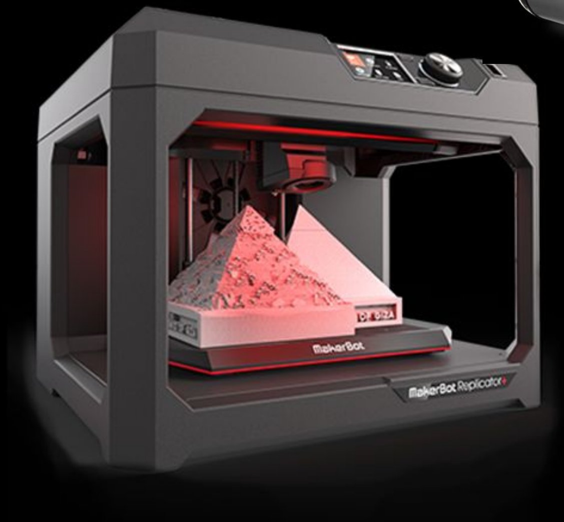
Those these brackets could be made through die casting, it is far more economical to produce via extrusion.

Extrusion: how to identify?

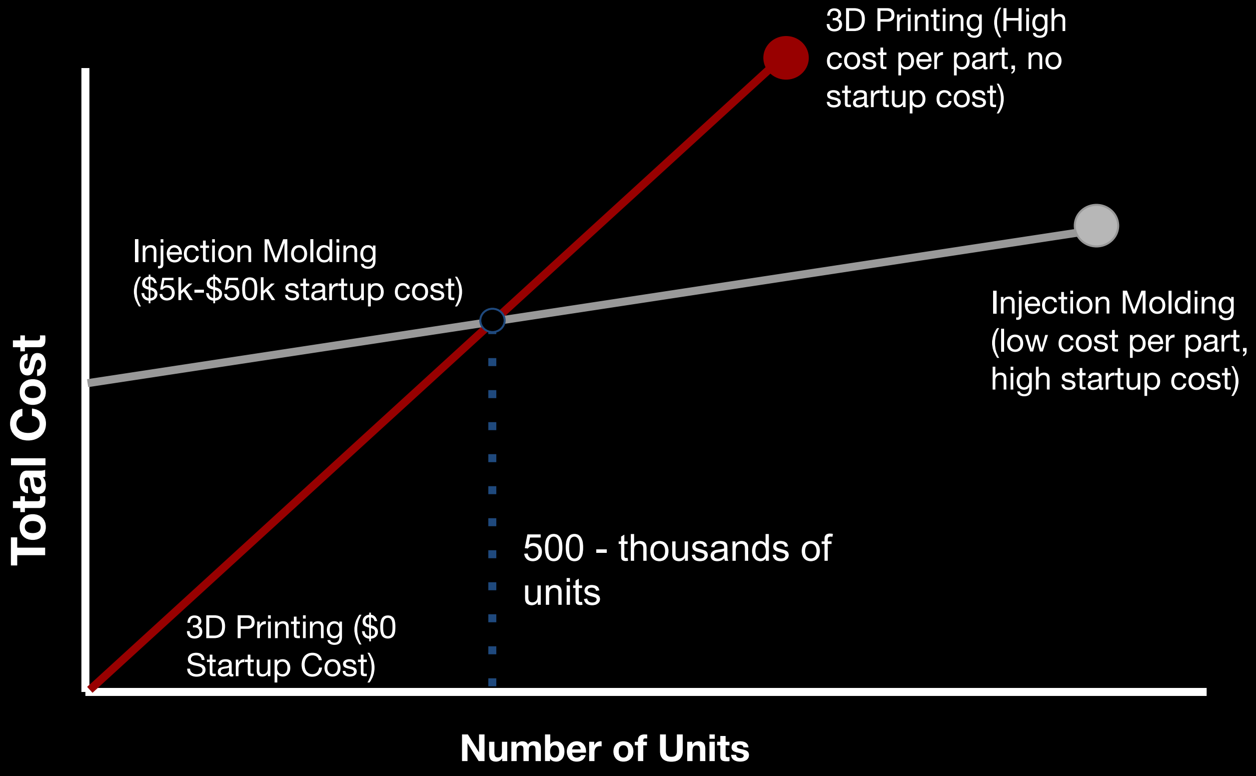
Very simple to identify - a common cross section.

3D Printing

- **Virtually anything that could be produced through injection molding could be made through 3D printing.** However, cost and volume wise, 3D printing is the inverse of injection molding.
- With 3D printing there is virtually no fixed cost (compared to injection molding which can cost thousands of dollars for mold to be made).
- Injection Molding has a low cost per unit, but 3D printed objects can be expensive per unit by comparison.
- The last variable to is time. It can take hours to days to print an object. Whereas injection molded parts can take a couple seconds to minutes to produce.

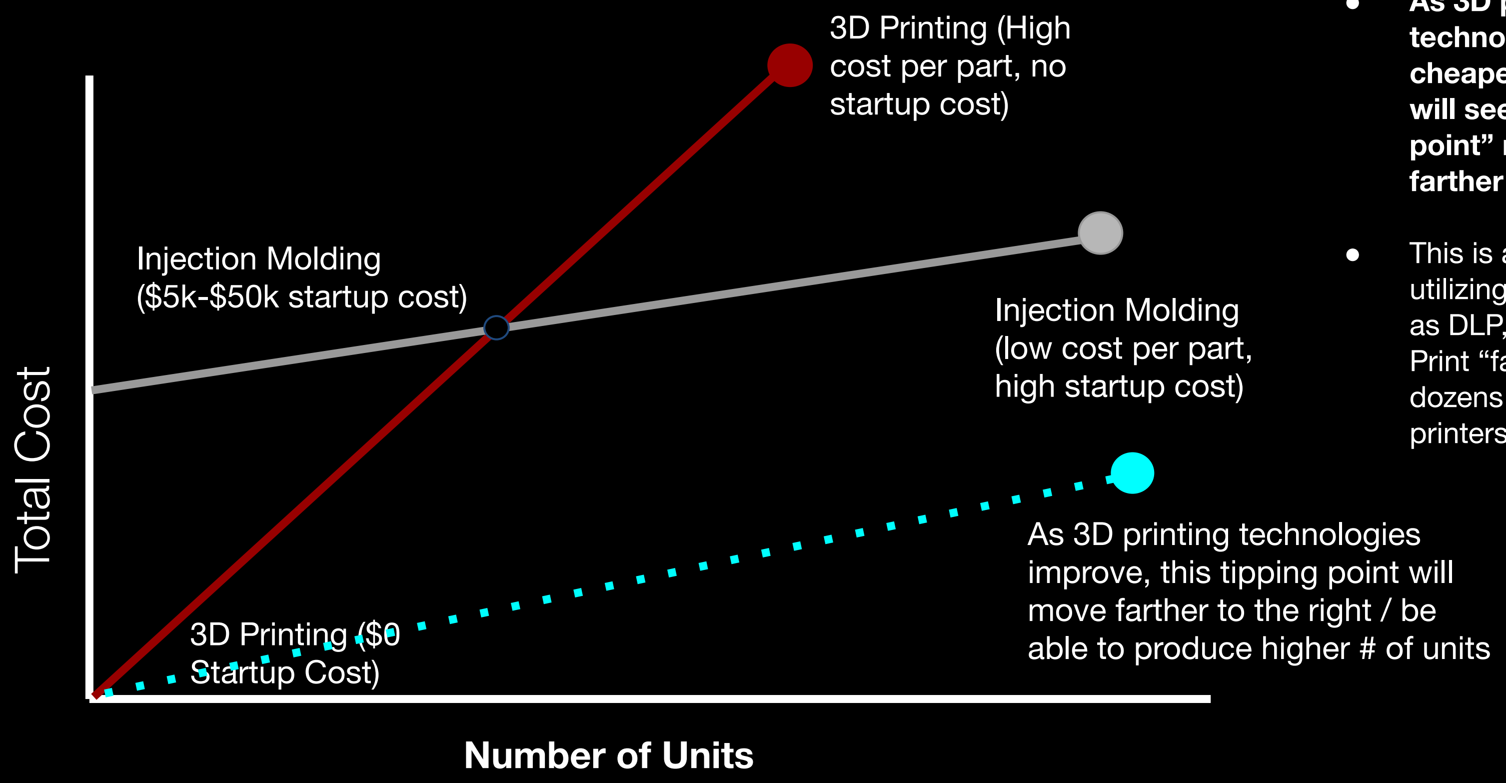


Injection Molding vs. 3D Printing



- **This "tipping point" graph visualizes when one should consider 3D printing vs. injection molding**
- It makes sense financially to utilize 3D printing if you intend to produce less than ~500 units, and to switch to injection molding if you intend to make ~thousands of parts.
- One factor this graph does not account for is time - 3D printing a part can take hours or days whereas injection molding can take seconds or minutes.

Injection Molding vs. 3D Printing



- **As 3D printing technologies become cheaper and faster, we will see this "tipping point" move farther and farther to the right.**
- This is already happening utilizing technologies such as DLP, or through the 3D Print "farms" that utilize dozens or hundreds of printers at once.

Manufacturing Processes can be broken down into three categories describing the way in which material is transformed into a part/product.

Additive technologies refer to raw material being inputted in one form and then casted or “added” together to form an object.

Subtractive technologies refer to an input of a larger block of material that is then cut away/subtracted from to form an object.

Forming (or Net Forming) refers to objects that are made through manipulation of an input material through cutting, bending, and other manipulation techniques.

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- Injection Molding
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Subtractive

- Milling/CNC
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Deformative

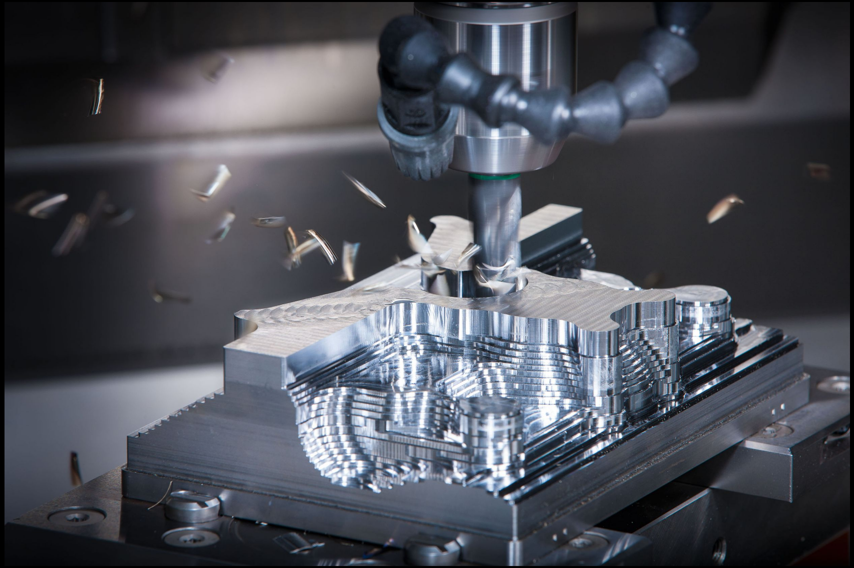
- Vacuum Forming
- Blow Molding
- Stamping

Milling and CNC

- Milling (or machining) is where a block of material is progressively cut away from using cutting tools.
- Computer Numeric Controlled (CNC) milling is a automated and computerized version of milling
- Plastics, metals, woods, and foams can be milled.
- Mills can generally only cut on one axis, meaning they can only move left/right/up/down.

Milling: Materials

- **Material: usually Aluminum.** Soft, strong and lightweight.
- **Consider: Waste** of subtracted material, recyclability
- Like injection molding vs. 3D printing, milling and die casting have an inverse relationship. Virtually anything that can be milled can also be die cast.
- **Consider: Time**
  - Milling: multiple hours, high use of human labor
  - Die casting: less time, more automated



An aluminum part being machined.

Milling: Pricing

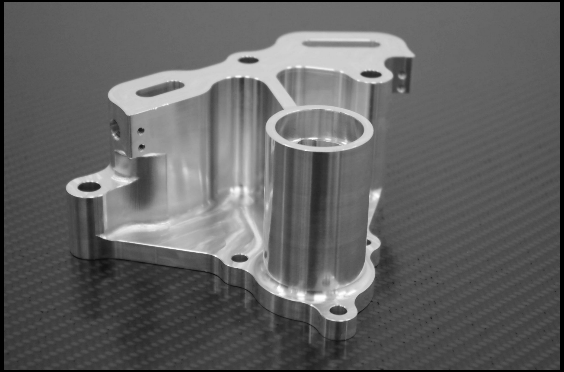
- Human labor. When milling, a highly trained machinist is paid to create each part. For CNC, a human still sets up the operation.
- No cost needed for mold production.
- Custom made jig also incurs some cost, though overall the set up pricing for a milling operation is low.

A machinist milling a part.

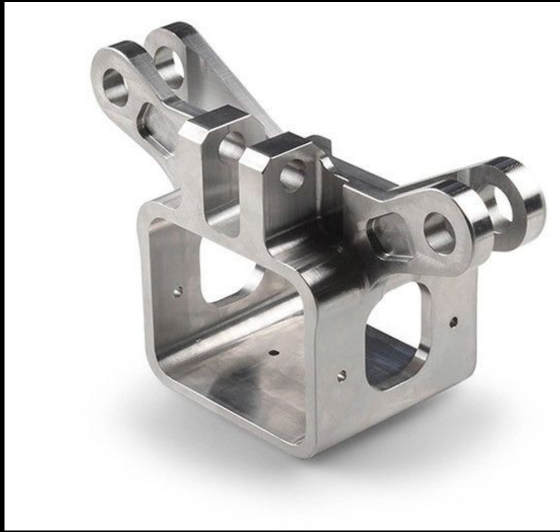
An industrial CNC machine.

Milling: Constraints

- Generally one is constrained to creating 2D extruded forms through milling.
- A part can be rotated and milled in multiple operations, though this adds to the cost per part.
- Hence this technology is appropriate for creating objects in the dozens or hundreds.

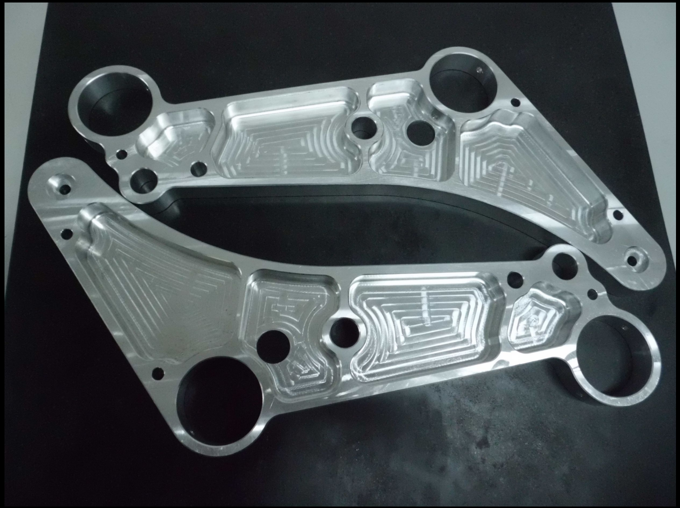


A part machined on one axis.



A part machined in multiple operations and axes.

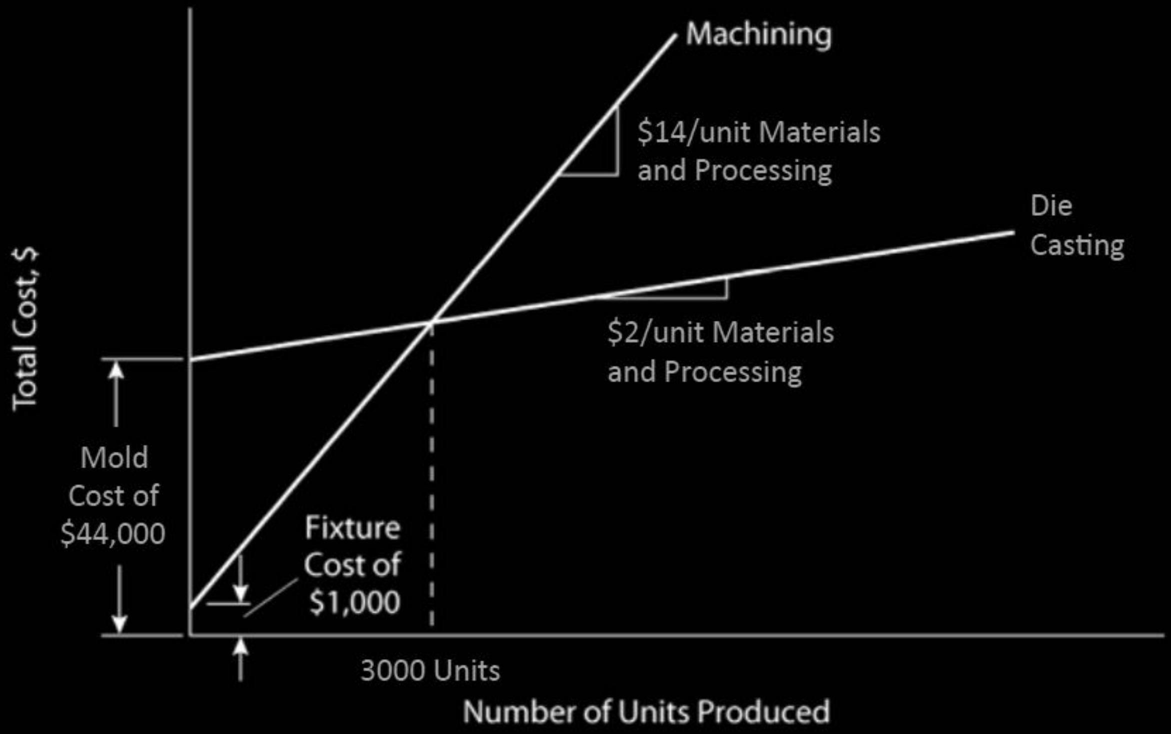
Milling: how to identify?



Tooling marks are an artifact left over from the cutting process. They follow the path of the cutting tool moving over the material. If desired they can be removed in post processing.

Simple 2D extruded forms are also a tell tale sign of a milled object.

Die casting vs. machining



This “tipping point” graph visualizes when one should consider maching a part vs. die casting it.

The two biggest factors are startup costs vs. number of units.

It makes sense financially to utilize milling if you intend to produce less than ~3,000 units, and to switch to die casting if you intend to make more than ~3,000 of parts.

One factor this graph does not account for is time - milling a part can take hours or days whereas die casting can take minutes to hours.

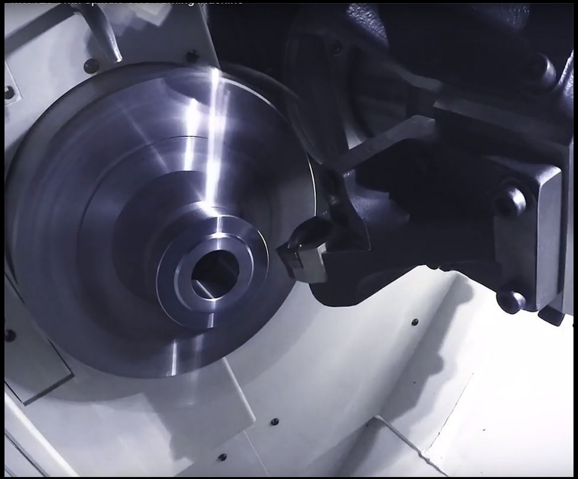
Turning

- Starts with a larger block of material which is progressively cut away from to create a part/object.
- The block of material is turned at a high speed and then cut away from.
- This produces parts that are radially symmetric - symmetric around a central axis.

Turning: Materials

- Soft materials like aluminum and woods
- Creates a lot of unused waste material
- Like injection molding vs. 3D printing, turning and die casting have an inverse relationship. Virtually anything that can be turned can also be die cast.
- Time: turning can take multiple hours to create an object using a lot of human labor

wood turning



automated turning machinery

Turning: Pricing

- **Cost of human labor: high**
  - **Unautomated:** machinist makes each part
  - **Automated:** machinist sets up each block of material and each new operation
- **Cost: Custom jig** to hold material during turning process
- In comparison to die casting, the cost per part utilizing this technology is very high.

Human operated turning operation

Turning: Constraints

- **Constraint:** must be radially symmetrical
- If you can design your part to be radially symmetric, this can potentially save lots of cost vs. die casting.
- The turning process does not necessarily have to start with round stock - you could use hexagonal stock and only turn a portion to create a bolt
- Turning can also produce threaded or tapped objects.

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Subtractive technologies refer to an input of a larger block of material that is then cut away/subtracted from to form an object.

Subtractive

- Milling/CNC
- Turning

Forming (or Net Forming) refers to objects that are made through manipulation of an input material through cutting, bending, and other manipulation techniques.

Deformative

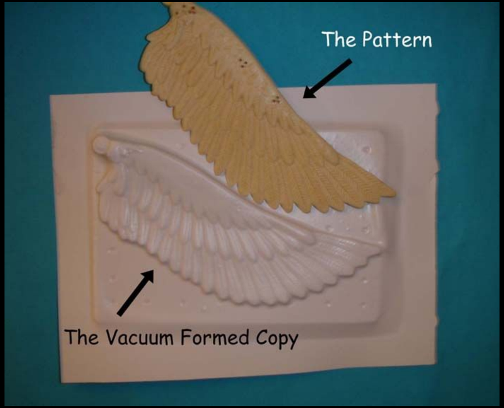
- Vacuum Forming
- Blow Molding
- Stamping

Vacuum Forming (Thermoforming)

- A thin sheet of plastic is first heated to its glass transition temperature (it is malleable, but not liquid).
- The sheet of plastic is then lowered onto a pattern (positive) in the shape of the object, and a vacuum is pulled under the hot plastic to “suck” it onto the shape of the pattern.
- Most commonly used for packaging (such as clamshell packaging).

Vacuum Forming: Materials

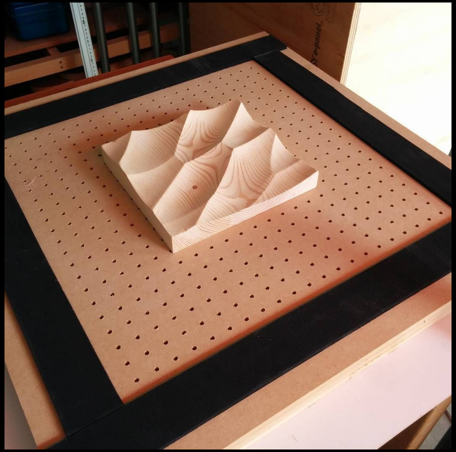
- Only thin sheets of plastic can be used. Styrene is often used because it is a plastic with a lot of resilience - meaning it can bend before breaking - which means it can come in very thin sheets.
- Acrylic can also be used in vacuum forming, but it is generally a plastic that comes in thicker sheets because it is not as resilient and is more brittle.
- However, the thicker the plastic, the less detail one can get through this process.



Examples of patterns and thermoformed objects.

Vacuum Forming: Materials

- A pattern (positive shape) for vacuum forming can be made out of CNC'd aluminum or steel. Lower cost patterns can be made out wood or foam.
- A softer material, such as wood, will allow comparatively few objects to be formed over it before the pattern degrades. Whereas with aluminum, many more objects can be formed before the pattern degrades.
- Inexpensive material
- Overall much cheaper than injection molding.



A pattern made from CNC'd wood.

An aluminum pattern.

Vacuum Forming: Constraints

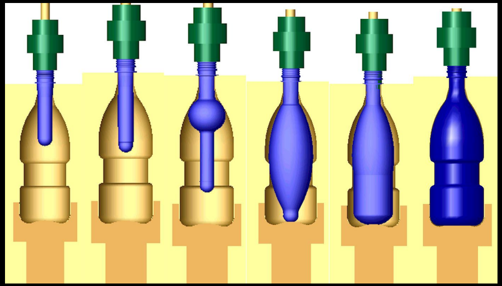
- The biggest design constraint with vacuum forming centers around the ability to get the object off the pattern.
- No undercuts, consider draft
- The scale for vacuum forming can range from something from an inch or two, to something very large like a bench or bus seat
- A unique plus to vacuum forming is that often multiple parts can be formed out of the same sheet at the same time. Additionally, parts are once piece that can fold over and clasp is easily achievable through vacuum forming.

Thin, clear plastic - clamshell packaging (below) candy molds made through vacuum forming

My vacuum formed brooch made using a piece of ginger!

Blow Molding

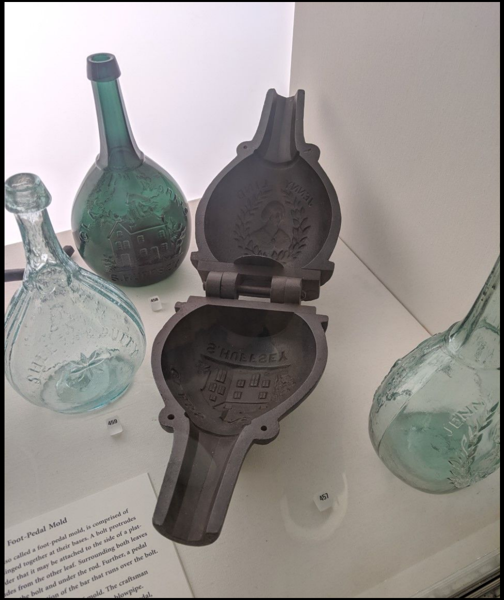
- Used to make hollow objects
- Air is blown into a heated malleable piece of plastic placed inside a mold and the plastic expands to fill the mold
- **Parison:** a smaller, thicker version of the object to be formed that gets placed inside the mold
- The mold that surrounds the parison is generally made from aluminum or steel. Functionally this mold is similar to an injection mold.

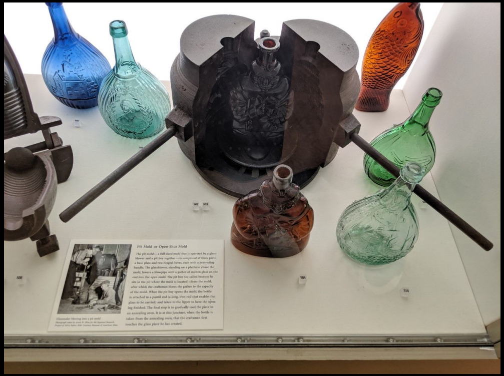


Blow Molding: Materials

- This basic principles of this process were actually borrowed from glass blowing - a process that was developed in the 1st century BC that is still used today!
- Most commonly used to produce disposable bottle packaging - soft drink bottles, detergent bottles, shampoo bottles
- HDPE, PETE, PP (polypropylene) are commonly used - translucent and thermal stable

Glassblowing molds at the PMA (dating from the late 1800s).





Blow Molding: Pricing

- If a cast parison is used, then there is added cost to creating an injection mold for the parison itself. Extrusion parisons can incur less costs.
- The bulk of the cost associated with blow molding is the final mold which is functionally similar to an injection mold.

Examples of cast (left) and extruded (right) parisons.

Blow Molding: Constraints

- Objects must be hollow
- Blow molded objects can range in size from a small bottle, to a large tub or barrel.
- Because of the cost of the mold and parison, it's most appropriate to utilize blow molding if the volume of objects is expected to be in the thousands to millions of units.
- Post processing can be done to blow molds to add additional holes (for example plastic watering cans).

Holes can be cut in the object during post-processing.

Example of large blow molded object.

Blow Molding: how to identify?

Disposable bottle packaging made of plastic. They are also thin walled, hollow, and have an opening on one side where the air was blown in.

Blow molded objects also often have parting lines - similarly to injection molding.

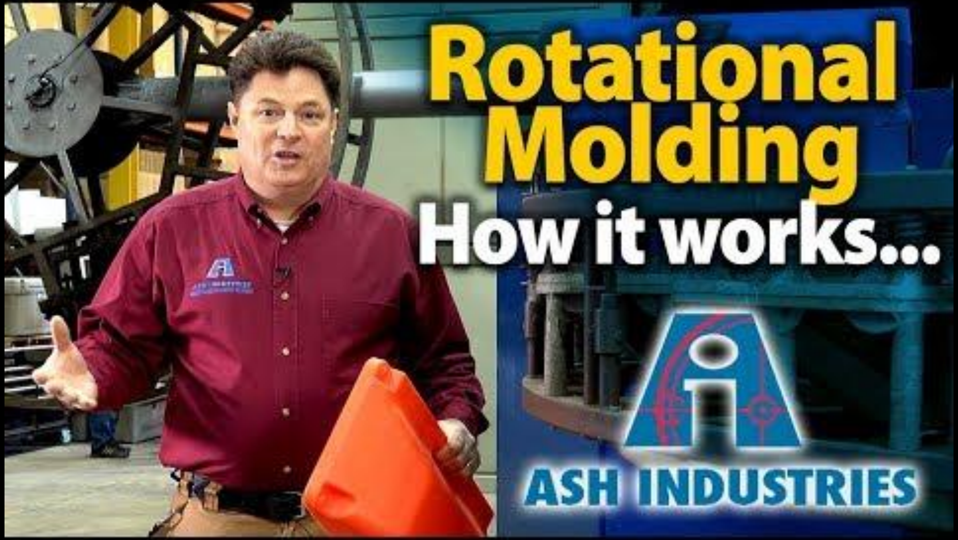
Rotomolding (Rotational Molding)

- Large, hollow plastic parts
- Parts can be completely enclosed since there is no need for an air hole.

The infamous Cozy Coupe - perhaps your first vehicle - is made through rotomolded vinyl.

Rotomolding

- Input is thermoset plastics - can't be remelted or separated so not easy to recycle
- Once the liquid plastic is put into the mold, the mold is slowly rotated as the plastic becomes hard to coat the walls of the mold.
- Note that the mold is not completely filled with liquid plastic - the mold is only filled with enough plastic to coat the mold with a desired thickness of material.
- Aluminum or steel mold - $1000s



Rotomolding: Materials

- **Biggest Pro:** ability to make large, hollow, and lightweight objects. The hollowness conserves material, which obviously also conserves material cost.
- A unique property of this hollow process is the ability to make buoyant objects such as boats, buoys, and life preservers.
- Vinyl toys such as those from Kid Robot, are a cool application of the rotomolding process.

Rotomolded buoyant objects + their molds

Rotomolded vinyl collectibles from KidRobot.

Rotomolding: Pricing

- High cost: mold
- Efficient way to make large objects
- Cost per part: low

A large rotomolding machine used for making 50 gallon barrels.

Rotomolding: Constraints

- **Objects must be hollow.** But in actuality this is the biggest plus and driver for choosing this technology.
- Because the liquid plastic sets up over time as the mold is rotated, this can cause some small inconsistencies in wall thickness on the inside of the object. Since this is not visible, it is not always an issue.
- However this would be unsuitable for some objects, such as a ping pong ball, where a consistent wall thickness dictates the predictability of the ball's bounce and spin.

Rubber duckie cut in half to show inconsistent wall thickness.

Oftentimes you can also see visible drips on the inside as an artifact from the casting process.

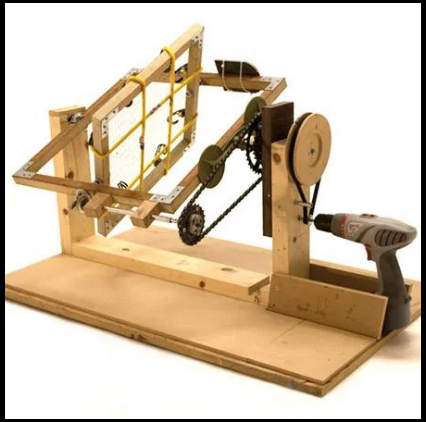
Rotomolding: how to identify?

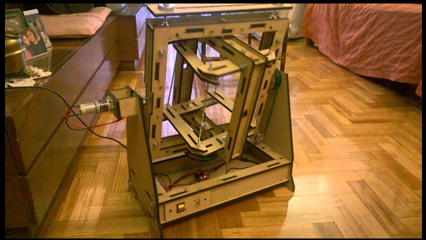
Soft, hollow rubbery toys.

Hollow objects that do not have holes/openings.

Large, lightweight, hollow objects.

DIY Rotomolding





Stamping

- **Material: sheet metal.** Many types of metal can be stamped but ferrous metals are rarely used since they are more prone to cracking when bent.
- Stamped parts are usually made through a combination of cutting, forming, and bending operations
- The process works by utilizing steel tools and dies to cut and bend the metal to the desired shape.
- A “die” is terminology used specifically to refer to molds and jigs that are used in forming operations that manipulate a material by applying pressure.

Stamping: Materials

- The biggest pro of utilizing stamping is the very low cost per part. If you can design a part to be stamped vs. die casted, it can save a lot of money per part and lower your start up costs.
- Stamped parts can be very strong, and are often used to create brackets and other load-bearing objects.

Stamped brackets that were later powder coated with black pigment.

A variety of stamped parts and objects.

Stamping: Materials

- The cost per part of a stamping operations can be very inexpensive...in some cases less than a penny per part.
- However, there is a relatively high start up cost associated with the cost of custom dies and the number of operations needed to create your part.

The difference is subtle, but the lockring on the left was stamped whereas the one on the right was die-cast.

Stamping: Constraints

- Metal is the only suitable material since it can bend and hold its shape without breaking.
- You must have continuous wall thickness, since you are constrained to whatever thickness of the stock that is being used - there can be no variation in the thickness.
- Lastly, there is a finite amount of operations that can be done to a single part because
  - The more a metal part is bent and manipulated, the more likely it is to crack or break
  - Complex undercuts and overhangs can prohibit any further manipulation of an object.

An example of a complex stamped object made through multiple cutting and forming operations.

Stamping: how to identify?

Metal objects with consistent wall thickness.

Objects that conceptually could be made through cutting and bending paper.

Brackets and joinery mechanisms.

Challenge Bag Activity

- Groups of four
- Grab a bag of products (standard or difficult)
- Identify how each part was made *and how you can tell*

Additive technologies refer to raw material being inputted in one form and then casted or “added” together to form an object.

Additive

- Injection Molding
- Die Casting
- Sandcasting
- Extrusion
- 3D Printing

Subtractive technologies refer to an input of a larger block of material that is then cut away/subtracted from to form an object.

Subtractive

- Milling/CNC
- Turning

Forming (or Net Forming) refers to objects that are made through manipulation of an input material through cutting, bending, and other manipulation techniques.

Deformative

- Vacuum Forming
- Blow Molding
- Stamping

Homework

- Lecture: Entrepreneurial Product Development
- Manufacturing Processes Individual Assignment
- Alpha Prototype Pitch next class
    - Due 10 AM day of class!

Coming Up

- 4/11: Alpha Prototype Pitch
- 4/18: Design Fair Prep Work Day
- 4/27: Design Fair!

Alpha Prototype Pitch

- Two minutes to present, two minutes for questions
- Two slides
- Polished alpha prototype

- Reintroduce your product
- Show off your prototype
- Reiterate customer needs if necessary
- We will be voting but no ideas will be eliminated!

Further Reading & Resources

Suggested Manufacturers:

Protolabs: Injection molding, sheet metal forming, milling, turning, and 3D printing (https://www.protolabs.com/)

Shapeways: 3D printing (https://www.shapeways.com/)

Xometry: milling, turning, sheet metal forming, water jet cutting, 3D printing, and injection molding (https://www.xometry.com/)

Hord Rapid Tools: injection molding, die casting, extrusion, milling, turning, and 3D printing (https://www.hordrt.com/)

Star Rapid: injection molding, milling, turning, 3D printing, die casting, and vacuum forming (https://www.starrapid.com/)

More can be found by searching for "low volume manufacturing"

Design for Manufacturability Resources:

Injection Molding:
https://www.protolabs.com/services/injection-molding/plastic-injection-molding/design-guidelines/
Die Casting:
https://www.dynacast.com/en/knowledge-center/multiple-design-solutions/die-cast-design/die-casting-manufacturability
Sand Casting:
https://sites.psu.edu/shapelab/files/2017/02/Trad_Casting_Rules_Santosh-2kkxcb8.pdf
Extrusion: https://elixirext.com/downloads/Die%20Design%20Elixir%20Industries.pdf
3D Printing: https://www.protolabs.com/services/3d-printing/

Milling: https://www.protolabs.com/services/cnc-machining/cnc-milling/design-guidelines/
Turning: https://www.protolabs.com/services/cnc-machining/cnc-turning/design-guidelines/

Vacuum Forming:
https://www.rayplastics.com/designing-thermoforming-design-guide-chapter-2/
Blow Molding: https://www.custom-pak.com/design/blow-molding-design-guide/
Stamping: https://www.esict.com/what-is-metal-stamping/

Other Cool Processes:

- **Soft goods / Clothes**
- **Dip Molding**
- **Ping Pong Balls**
- **Wire Bender**
- **Water Jet Cutting**


UK