









An Introduction to Design for Manufacture (DFM)

and our core manufacturing processes:

- Plastic Molding
- Sheet Metal
- Rapid Prototyping/3D Printing
- Bar & Tube Fabrication
- Metal Casting
- Machining

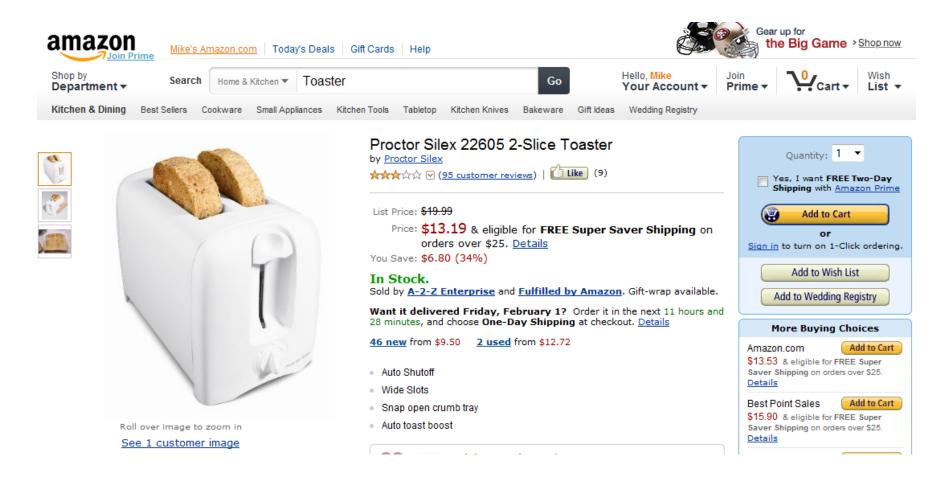
Instructor: Mike L. Philpott mphilpot@illinois.edu

Winners of the 2019 Shell EcoMarathon



Understanding Manufacturing Cost of Consumer Products

- predominantly Sheet metal and Injection Molded Plastic



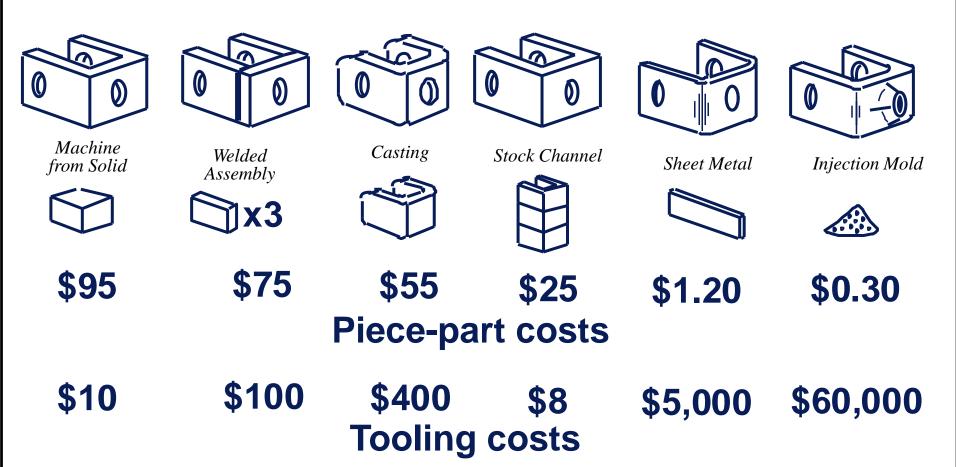
Look at retail prices...divide by 3!

Design for Manufacture (DFM) Overview

- Product Development teams need to know cost early in design to do what-if analysis and explore alternative designs before expensive hard tooling decisions finalized
- aPriori's integrated CAD/DFM software utilizes 3D CAD's mathematical definition of the part/assembly to provide instant cost estimates as you create geometry.
- Necessary today due to high overseas competition and overseas sourcing opotunities
- Need to know early if cost targets are being met redesign if necessary before its too late.

Design for Manufacture (DFM) Example

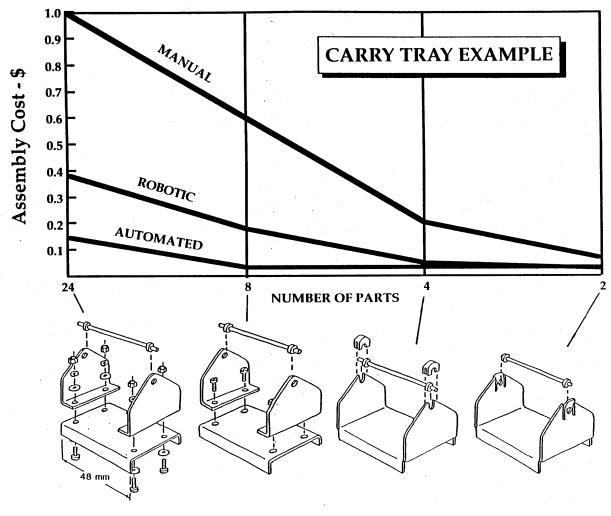
A simple fork end for Pneumatic Piston



Production Volume: Recurring Costs versus Non-Recurring Costs

Design for Assembly (DFA)

Fewer Parts generally means lower overall mfg.cost

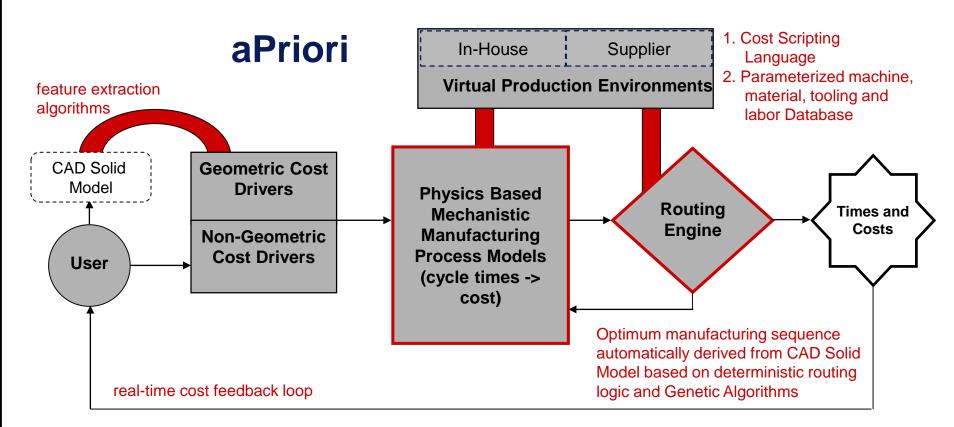


Number of Parts:

Assembly Time (s): 100

Feature Based Costing (FBC) Research

- CAD-integrated feature recognition and extraction methodology to provide engineers with accurate real-time cost feedback during design.
- Industry/University Collaborative research project: Started in 1992 with UIUC / John Deere Collaboration - now commercialized <u>www. aPriori.com</u>*



^{*} Philpott, M.L., "Integrated Real-Time Feature Based Costing (FBC)," U.S. Patent No. 7,065,420, June 20, 2006

Cost Accounting

Insights and Cost Reduction Opportunities

Cost Statement - Calculated Results (one process, one part)

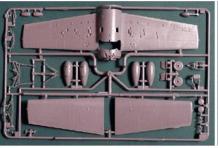
Cost Statement - Calculated F	Results (d	one process, one part)
Direct Variable Costs:		
Material Cost	\$1.22	 Part Weight * Raw Material Cost Per Kg / Material Utilization
Labor Cost	\$0.36	= Labor Time * Labor Rate
Direct Overhead	<u>\$0.47</u>	Cycle Time * Labor Rate* Overhead Rate
Subtotal	\$6.00	= Material Cost + Labor Cost + Direct Overhead
Expendable Tooling	\$0.11	= Expendable Tooling Cost
Set-up costs	\$0.27	= Set-upTime * LaborRate / (AnnualVolume * NumberOfParts / BatchesPerY
Additional Direct Costs	<u>\$0.00</u>	= Additional Direct Costs (none)
Other Direct Costs	\$0.38	= Expendable Tooling + Set-up Costs + Additional Direct Costs
Piece Part Cost Direct Fixed Costs:	\$6.38	= Material Cost + Labor Cost + Direct Overhead + Other Direct Costs
		AmortizationVolume =
		AnnualProductionVolume*NumberOfParts*ProductLife = 5,000
Direct Fixed Costs:		
Hard Tooling	\$3.00	CapitalTooling / (AmortizationVolume)
Fixtures and Jigs	\$0.00	CapitalFixtures&Jigs / (AmortizationVolume)
Programming Cost	\$0.03	= ProgrammingTime * LaborRate / (AmortizationVolume)
Amortized Investment	\$3.03	 Hard Tooling + Fixture and Jigs + Programming Cost
Total Cost	\$9.42	= Piece Part Cost + Amortized Investment

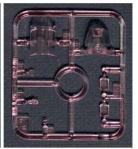
Plastic Molding

Injection Molding: Standard IM, Structural Foam Molding.

Reaction Injection Molding (RIM)













KEY COST DRIVERS

- Wall Thickness (typical: 1-2mm)
- Undercuts side Actions in the mold
- Number of cavities in the mold

Structural Foam Molding

Thick parts => 1/4 inch (6mm)



Blow Molding and Rotational Molding

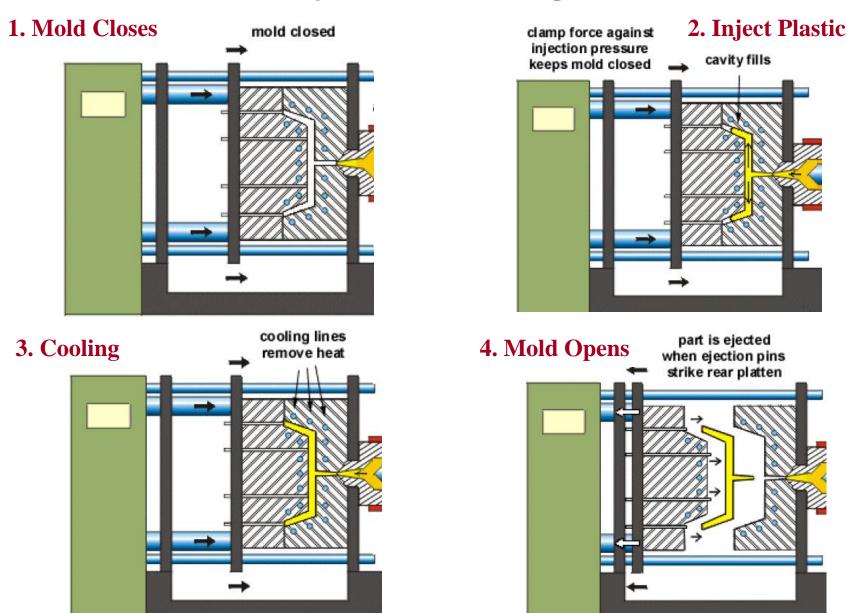


Blow molding
Bottles and small disposable containers



Rotational molding larger hollow shapes.

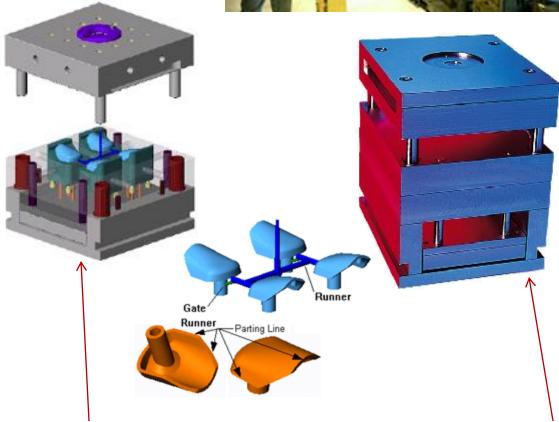
Injection Molding

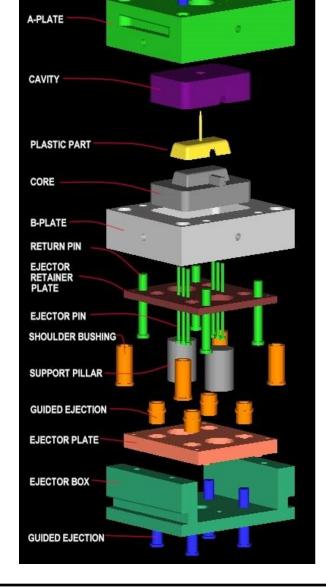


Labor Cost = (Mold Close time + Injection Time + Cooling Time + Mold Open time) * \$/hr rate

The Mold (Tooling)





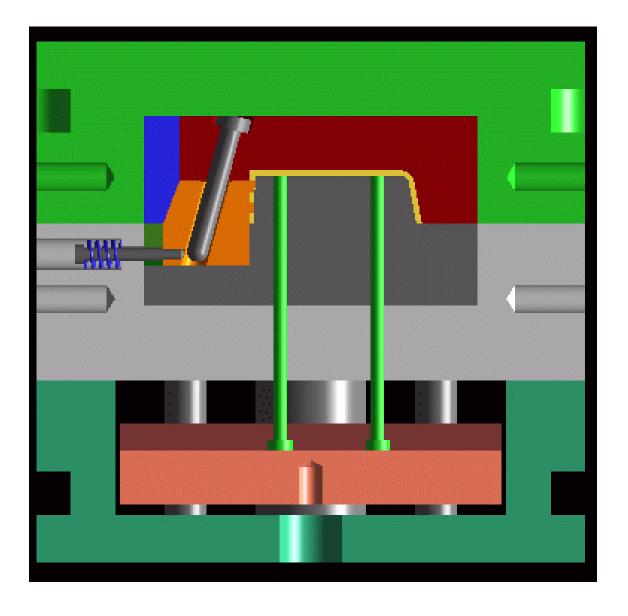


LOCATING RING

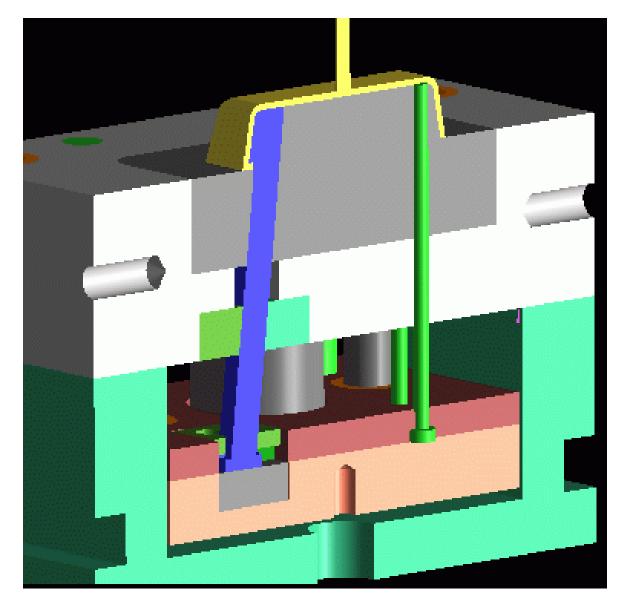
SPRUE BUSHING

LEADER PIN

Tooling Cost = Cost to design and build this mold tool

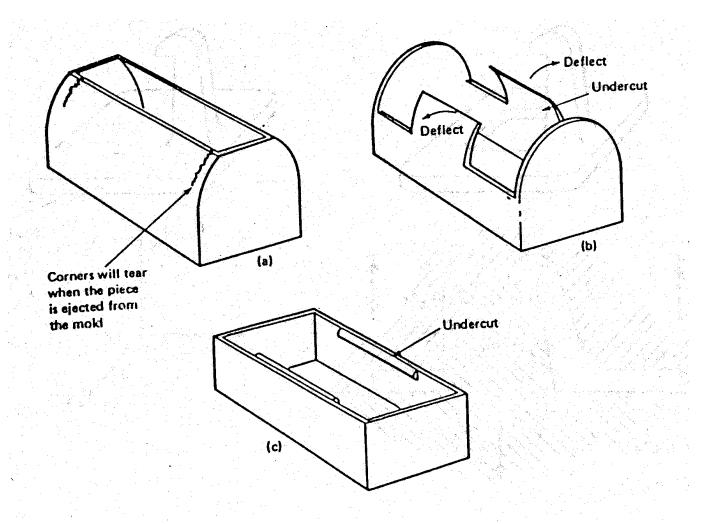


Moving Side Cores or 'Slides'

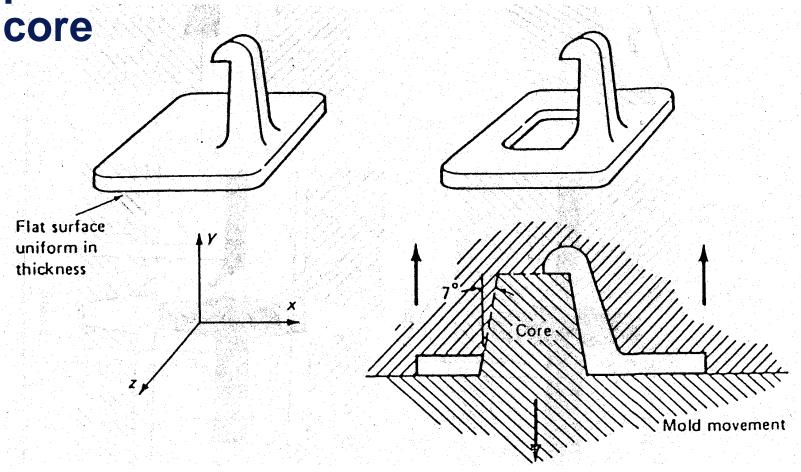


Moving Internal Cores or 'Lifters'

Avoiding Moving Side Cores and Lifters (1) – allow feature to deflect as part is ejected from the mold



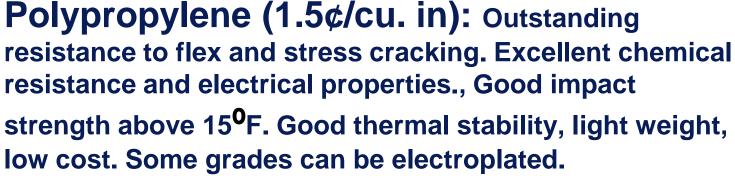
Avoiding Moving Side Cores and Lifters (2) – provide relief hole for



| Common Thermoplastic | Materials (1)

Polyethylene - HDPE & LDPE (1.2¢/cu. in)

Lightweight, easy to process, low cost material. Poor dimensional stability and heat resistance. Excellent chemical resistance and electrical properties.



Polystyrene (1.7¢/cu. in): Low cost, easy to process, rigid, crystal-clear, brittle. Low moisture absorption, and heat resistance. Poor outdoor stability.











PS

Resin Plastic Recycling Codes			
Resin Code	Technical Name	Typical Uses	
PETE	PETE, Polyethylene Terephthalate	soft drink bottles, deli trays, Mylar film, clear shampoo bottles, mouthwash bottles.	
ADPE HDPE	HDPE, High-Density Polyethylene	Tupperware, milk jugs, dishwashing detergent containers, juice containers, opaque shampoo bottles, oven cleaner bottles, insecticide bottles, yogurt containers	
<u>ئ</u>	PVC, Polyvinyl Chloride	plumbing pipes, construction materials, vinyl records, opaque shampoo bottles,	
4 LDPE	LDPE, Low-Density Polyethylene	grocery bags, dry cleaning bags, aquarium tubing.	
253 PP	PP, Polypropylene	appliance parts, Tic Tac hinge lids, drinking glasses, mustard squeeze bottles, margarine containers, pudding containers	
<u></u>	PS, Polystyrene	styrofoam cups.	
OTHER	Other plastics, including acrylic, polycarbonate, nylon, Kevlar, fiberglass.	compact discs, DVDs.	

| Common Thermoplastic Materials (2)

PVC (2.2¢/cu. in):

Rigid grades are hard, tough, and have excellent electrical properties, outdoor stability, and resistance to moisture and chemicals. Flexible grades are easier to process but have lower properties. Heat resistance is low, and low cost.



ABS (2.9¢/in3): Very Tough, hard, and rigid. Fair Chemical resistance. Low Water absorption and good dimensional stability. High abrasion resistance. Some grades are easily electroplated.

Acrylic (3.1¢/cu. in) Hard, glossy surface and high optical clarity. Fair Chemical resistance. Excellent resistance to outdoor weathering. Available in brilliant, transparent colors. Excellent electrical properties.

| Common Thermoplastic | Materials (3)

PETE (4.9¢/cu. in)

Crystal clear and hard. Used widely for shampoo bottles. Good moisture, and chemical resistance. Good dimensional stability.



Other

Acetal (5.8¢/cu. in)

Very Strong, stiff, and low tendency to stress crack. High resistance to chemicals. Retains most properties when immersed in hot water. Exceptional dimensional stability. High abrasion resistance. Low coefficient of Friction.

Polyurethane (6.1¢/cu. in)

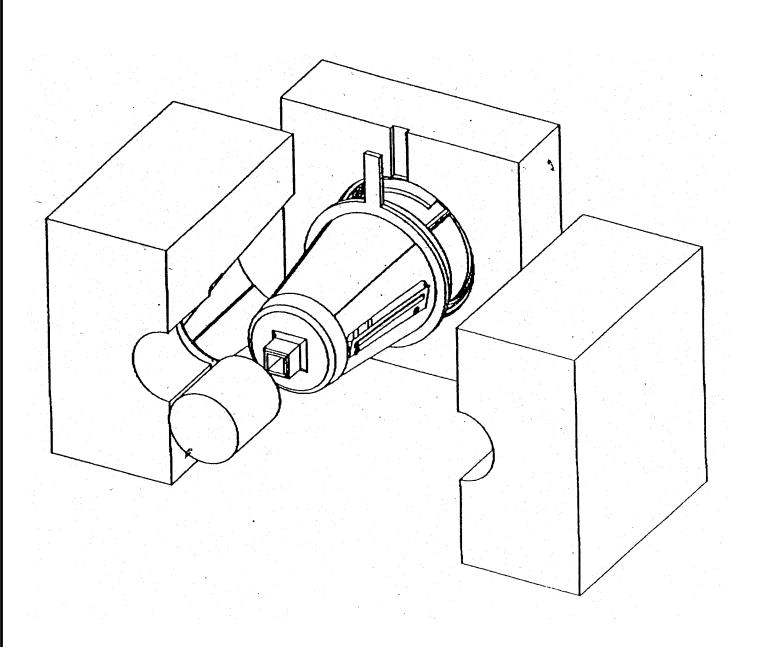
Tough, extremely abrasion and impact-resistant. Good electrical properties and chemical resistance. UV exposure causes brittleness, lower properties, and yellowing.

| Common Thermoplastic | Materials (4)

Nylon (6/6-5.9 ¢/cu. in;6/12 - 9.0 ¢/cu. in; +glass -16.3¢/cu. in): Family with outstanding toughness and wear resistance. Low Coefficient of Friction. Excellent chemical resistance and electrical properties. Hygroscopic; dimensional stability is poor. Some grades are electroplatable.

Polycarbonate (6.3 ¢/cu. in): Highest impact resistance of any rigid, transparent plastic. Excellent outdoor stability and resistance to creep under load. Fair chemical resistance. Some aromatic solvents cause stress cracking.

Fluoroplastics (30 - 65¢/cu. in): PTFE, FEP, PVDF etc. Family of high cost, low-to-moderate strength. Excellent chemical resistance. Low Friction. Outstanding stability at high temperatures.



Separate parts v. Molded-in hinges

Consumer products – rarely used as not economic; too many parts. Long assembly times screwing fasteners in etc



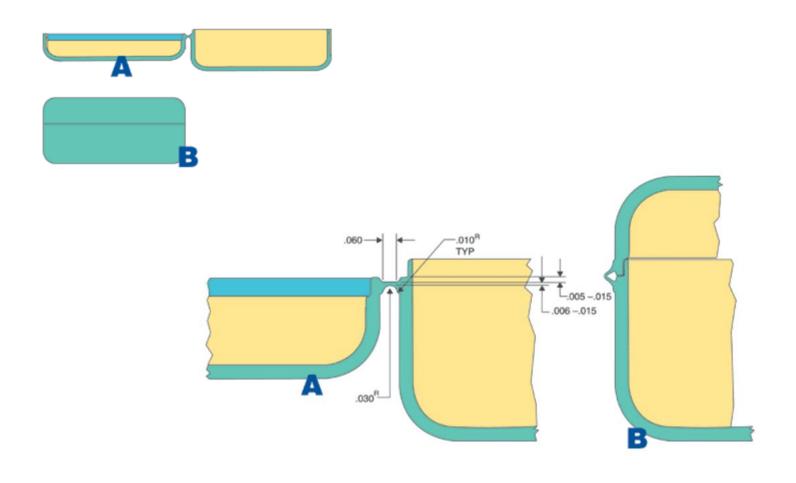




Molded-in hinges, snap fits, living hinges...more cost effective

Living Hinges

Single mold rather than two....limited to polypropylene for durable hinge life



https://www.plasticstoday.com/materials/design-polypropylene-part-design-part-2-living-hinges/2085268932270

Molded-in Hinges and flexible joints





Molded-in Hinges

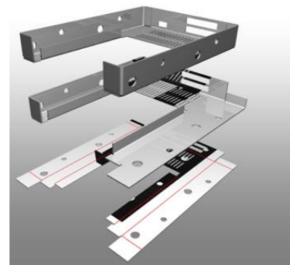






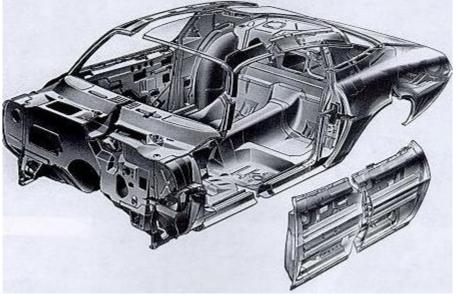


Sheet Metal Process Group









Sheet Metal – Common Production Processes

Soft Tooling - general purpose programmable machines with low-cost expendable tooling

Typical Routings: (as in aPriori)

Sheet Stock ⇒ Laser cut ⇒ [Bend Brake]

Sheet Stock ⇒ Plasma cut ⇒ [Bend Brake]

Sheet Stock ⇒ Water Jet ⇒ [Bend Brake]

Sheet Stock ⇒ Turret Press ⇒ [Bend Brake]

Hard Tooling (aka Stamping) - Processes requiring custom made high-cost molds or die sets

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Production Sheet Stock ⇒ Standard Press

Rate Sheet Stock ⇒ Stage Tooling (aka Tandem die)

Sheet Stock ⇒ Transfer Press Large Stampings (eg car Body Panels)

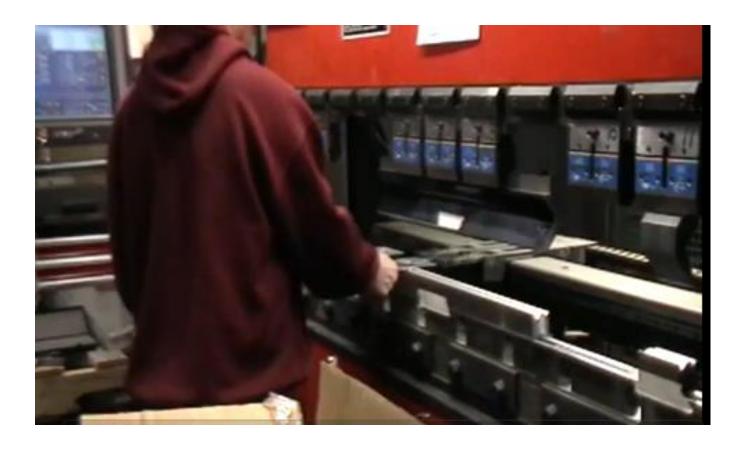
Coil Stock ⇒ Progressive Die Small Stampings
```

Laser Cuting



Bend Brake Process

'Soft Tooling' for straight bends – No Custom Tooling (ie no Hard Tooling)



Bend Brake (aka Press Brake)

Turret Press Process

'Soft Tooling' for straight bends – No Custom Tooling (ie no Hard Tooling)



Turret Press

Bend Brake – safety!



Sheet Metal – Common Production Processes

Soft Tooling - general purpose programmable machines with low-cost expendable tooling

Typical Routings: (as in aPriori)

Sheet Stock ⇒ Laser cut ⇒ [Bend Brake]

Sheet Stock ⇒ Plasma cut ⇒ [Bend Brake]

Sheet Stock ⇒ Oxy Fuel ⇒ [Bend Brake]

Sheet Stock \implies Turret Press \implies [Bend Brake]

Hard Tooling (aka Stamping) - Processes requiring custom made high-cost molds or die sets

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Production Sheet Stock ⇒ Standard Press

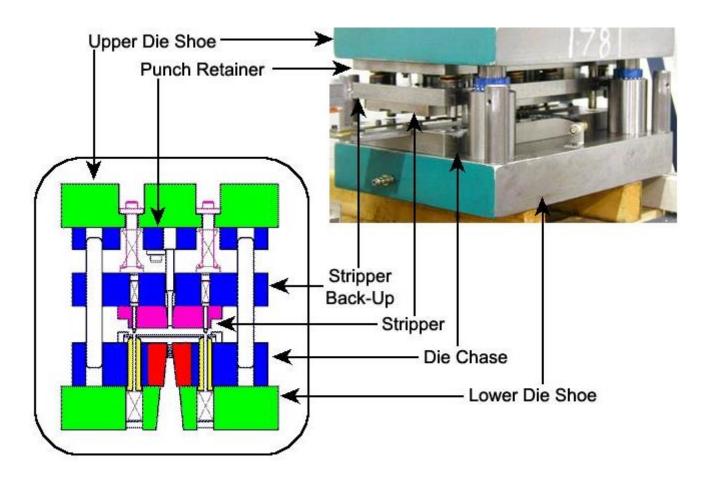
| Sheet Stock ⇒ Stage Tooling (aka Tandem die) |
| Sheet Stock ⇒ Transfer Press | Large Stampings (eg car Body Panels) |
| Coil Stock ⇒ Progressive Die Small Stampings
```

Progressive Die – coil fed, automatic, high-speed single press with multiple stations; coil strip transfers the part



Hard Tooling

Sheet Metal - Progressive Die Set



Progressive Die Tool – a tool custom designed and built to produce stamped metal parts at high speed on a Progressive Die Press (a reciprocating press)

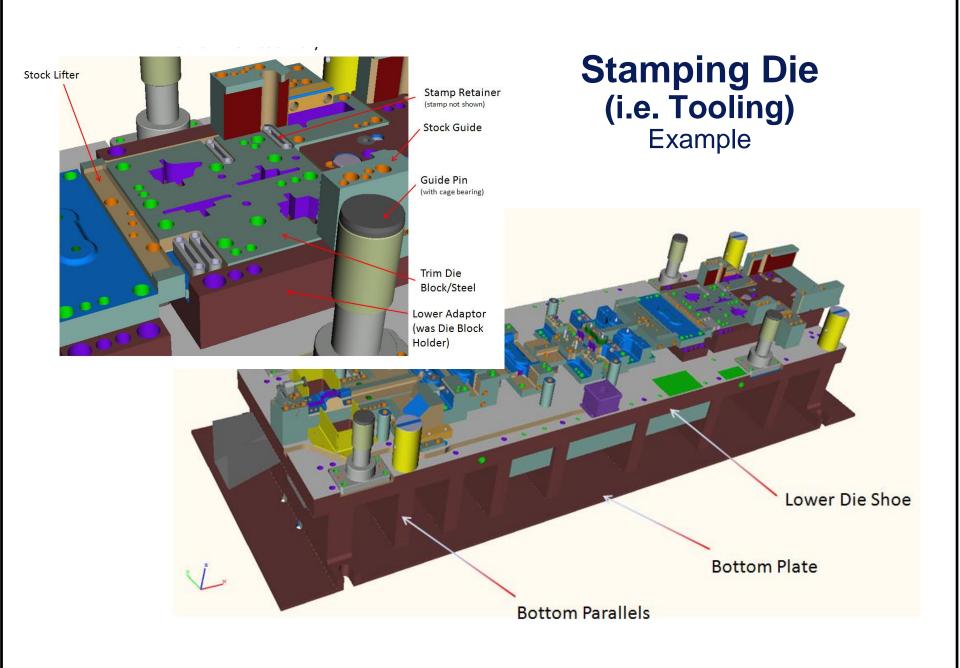


Progressive Die in Operation – 30 ppm



Progressive Die in Operation – 100 ppm

Used for Small High-Volume Stampings



Standard Press - manual presses operated in batch mode, typically low-to-medium volume applications



Stage Tooling – manual presses organized in a production line with manual transfer of parts between presses (popular in low labor cost



Manual Transfer inside a Press!

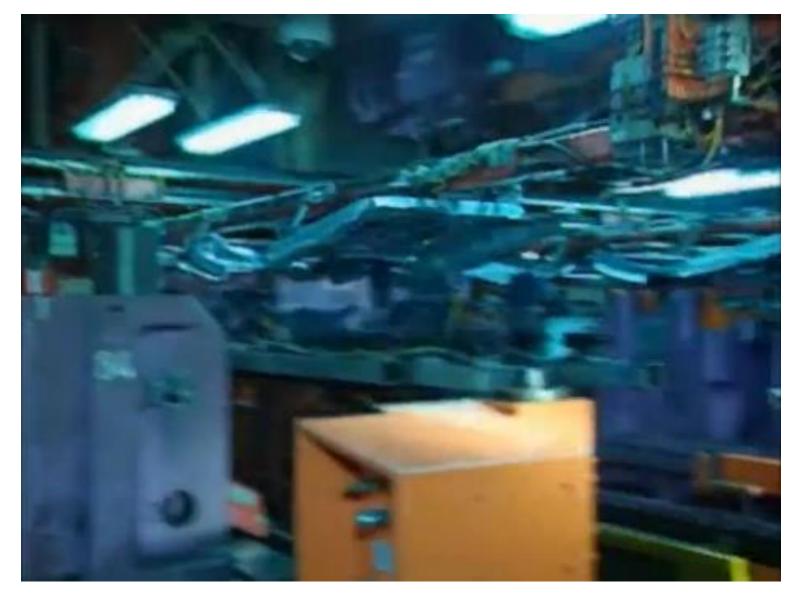


Tandem Die - manual or automatic presses organized in a production line manual or robotic transfer of parts between presses (often a mix of manual or robotic)



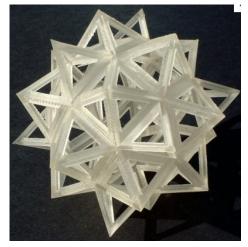
Transfer Press – sheet fed, single press action with multiple dies attached to platen and transfer mechanism



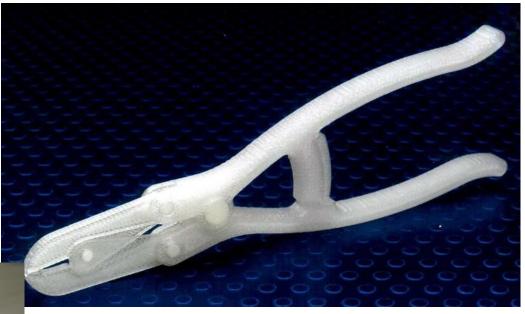


Transfer Press in Operation

Used for Large High-Volume Stampings





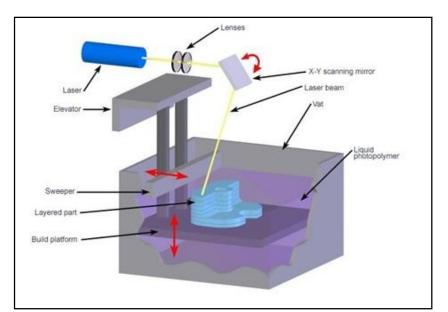


Rapid Prototyping Process Group

SLA

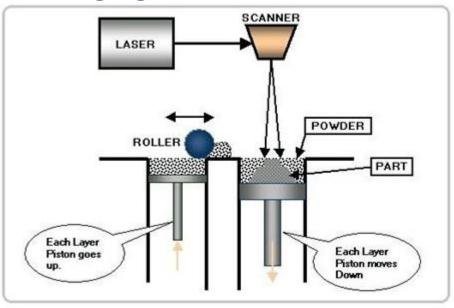
Rapid Prototyping Principles

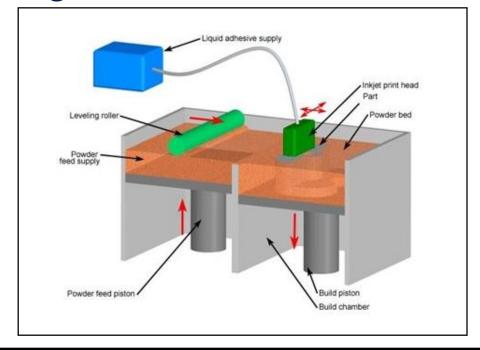
http://www.quickparts.com MechSE Rapid Prototyping Lab



3D Printing

SLS

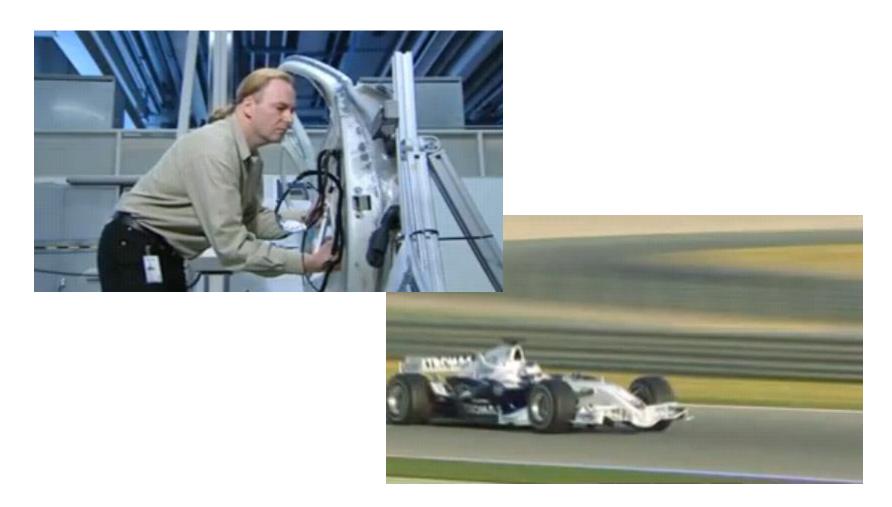




Rapid Prototyping Systems

- StereoLithography (STL)
- Selective Laser Sintering (SLS)
- Fused Deposition Modeling (FDM)
- Polyjet 3D Printer
- Composite 3D printer
- Direct Metal Laser Sintering (DMLS) on order
- Laminated Object Manufacturing
- Hot Plot
- Solid Ground Curing
- Light Sculpting
- Solid Creation System
- Solid Object Ultra-Violet Laser Plotting
- Computer Operated Laser Active Modeling
- Electro-Optical Systems Stereos

Rapid Prototyping at BMW



Cool video (click on pics)

Rapid Prototyping MechSE Ford Lab



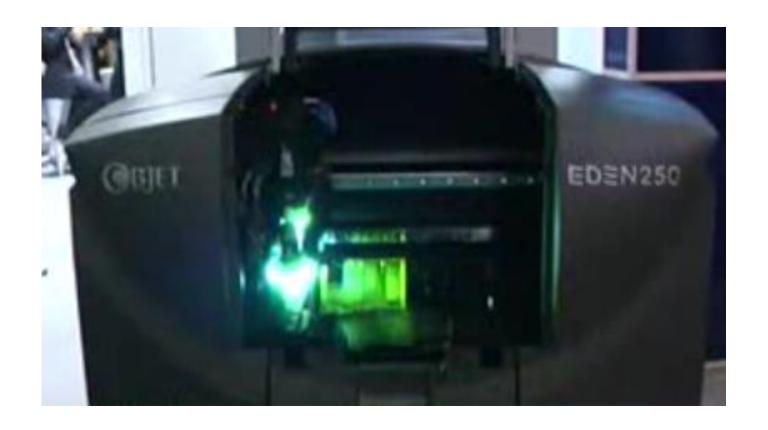


Meet the Mark One: the world's first Carbon Fiber 3D printer ...

Stereo-Lithography Apparatus (SLA)



Polyjet Process



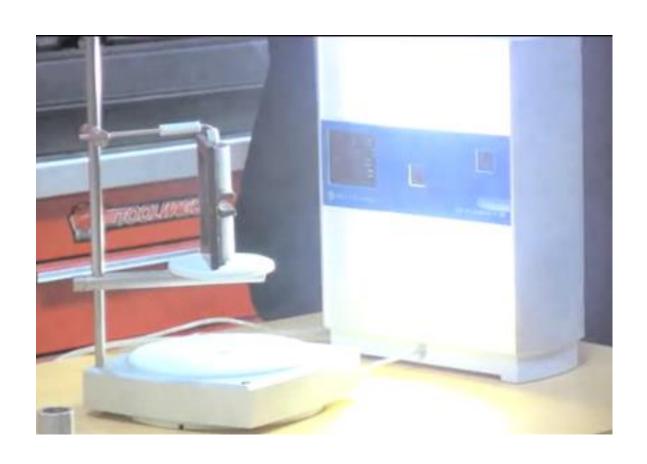
SLS - Sintered Laser System



EOS – Direct Metal Laser Sintering



3D Scanning & FDM – Fused Deposition Modeling



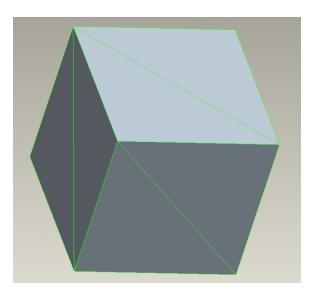
STL Format: B-rep, solid object

- ❖ An STL file is saved with the extension ".stl," case-insensitive.
- STL is a triangular facet based representation that approximates surface and solid entities only. Entities such as points, lines, curves, and attributes such as layer and color will be ignored during the output process
- ❖ An STL file consists of a list of facet data.
- * Each facet is uniquely identified by a unit normal (a line perpendicular to the triangle and with a length of 1.0) and by three vertices (corners).
- * The normal and each vertex are specified by three coordinates each, so there is a total of 12 numbers stored for each facet.

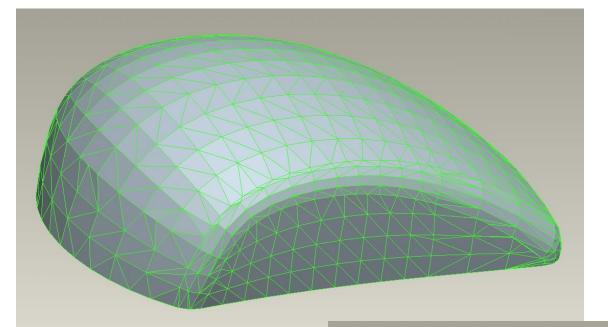
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BLOCK
facet normal 0.000000e+00 -1.000000e+00 0.000000e+00
 outer loop
  vertex 0.000000e+00 0.000000e+00 -1.000000e+00
  vertex 1.000000e+00 0.000000e+00 0.000000e+00
  vertex 0.000000e+00 0.000000e+00 0.000000e+00
 endloop
endfacet
facet normal 0.000000e+00 0.000000e+00 1.000000e+00
 outer loop
  vertex 1.000000e+00 1.000000e+00 0.000000e+00
  vertex 0.000000e+00 0.000000e+00 0.000000e+00
  vertex 1.000000e+00 0.000000e+00 0.000000e+00
 endloop
endfacet
facet normal -1.000000e+00 0.000000e+00 0.000000e+00
 outer loop
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 endloop
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endfacet

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  outer loop
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   vertex 1.000000e+00 0.000000e+00 -1.000000e+00
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  endloop
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  outer loop
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   vertex 0.000000e+00 1.000000e+00 -1.000000e+00
  endloop
 endfacet
 facet normal -1.000000e+00 0.000000e+00 0.000000e+00
  outer loop
   vertex 0.000000e+00 1.000000e+00 -1.000000e+00
   vertex\ 0.000000e+00\ 0.000000e+00\ -1.000000e+00
   vertex 0.000000e+00 1.000000e+00 0.000000e+00
  endloop
 endfacet
facet normal 0.000000e+00 1.000000e+00 0.000000e+00
  outer loop
   vertex 1.000000e+00 1.000000e+00 -1.000000e+00
   vertex 0.000000e+00 1.000000e+00 -1.000000e+00
   vertex 0.000000e+00 1.000000e+00 0.000000e+00
  endloop
 endfacet
 facet normal 0.000000e+00 1.000000e+00 0.000000e+00
  outer loop
   vertex 1.000000e+00 1.000000e+00 0.000000e+00
   vertex 1.000000e+00 1.000000e+00 -1.000000e+00
   vertex\ 0.000000e+00\ 1.000000e+00\ 0.000000e+00
  endloop
 endfacet
endsolid BLOCK
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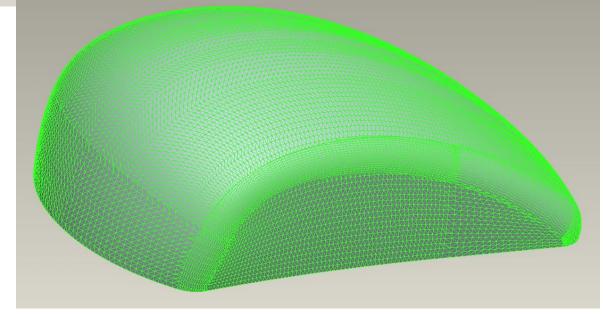


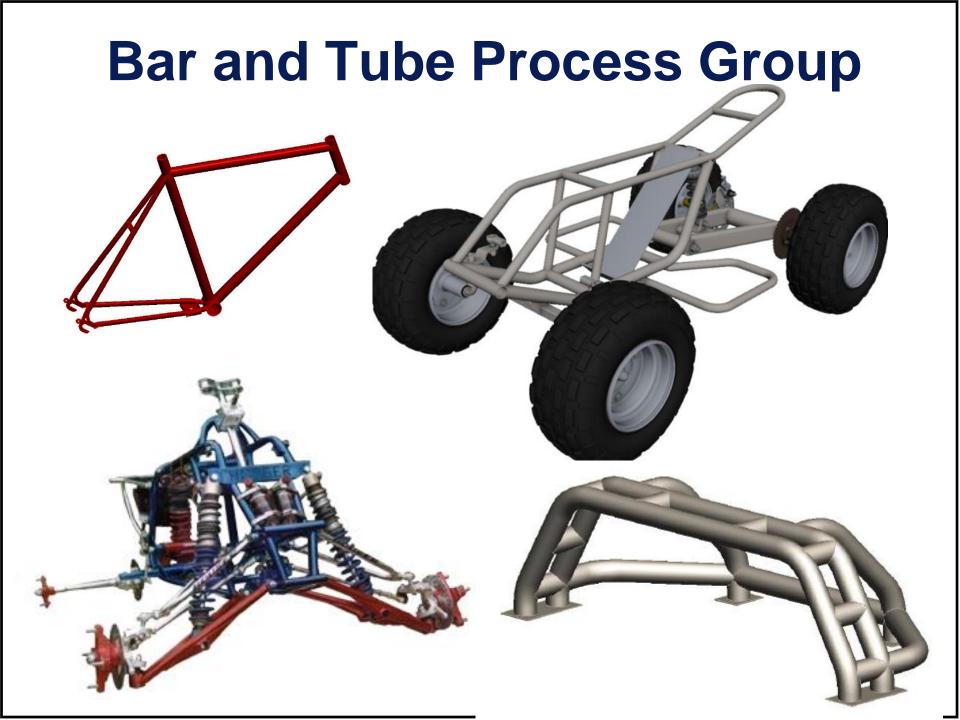
An Example STL File – Block.stl



The density of triangle facets change according to the geometry

And it Changes with Chord Height affecting final surface resolution





Tube/Bar Bending Processes Bend Brake (aka Press Brake)



Not suitable for Tube, only solid bar forms

Rotary Draw Bending

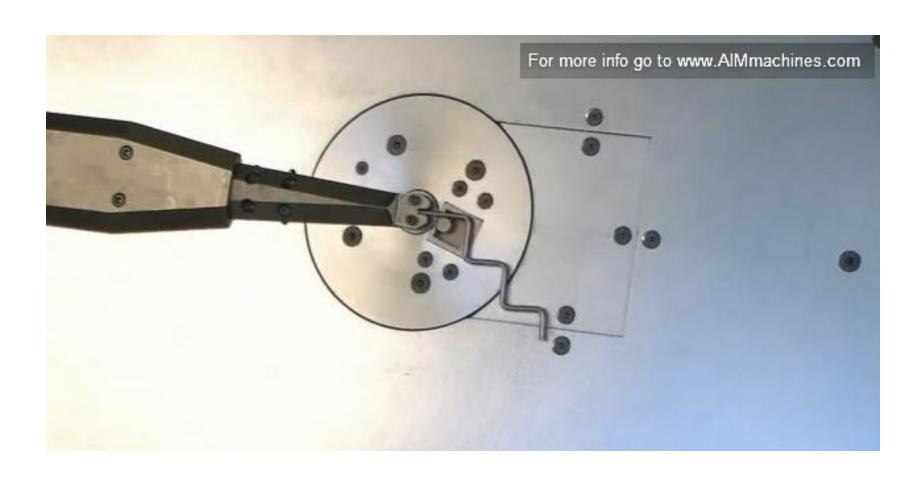


Rotary Draw Bending with Mandrel

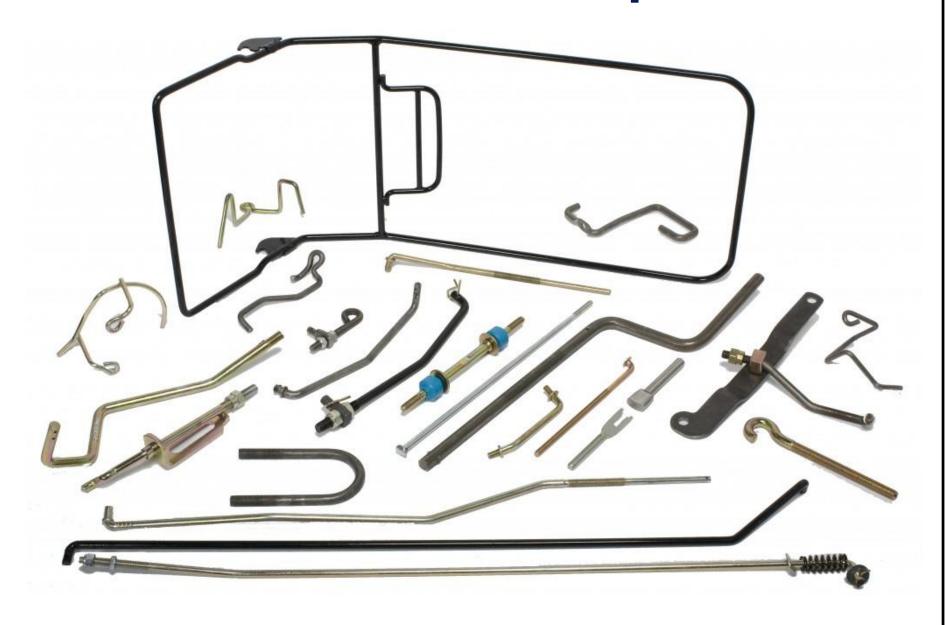


Reduces crushing of inner bend radius

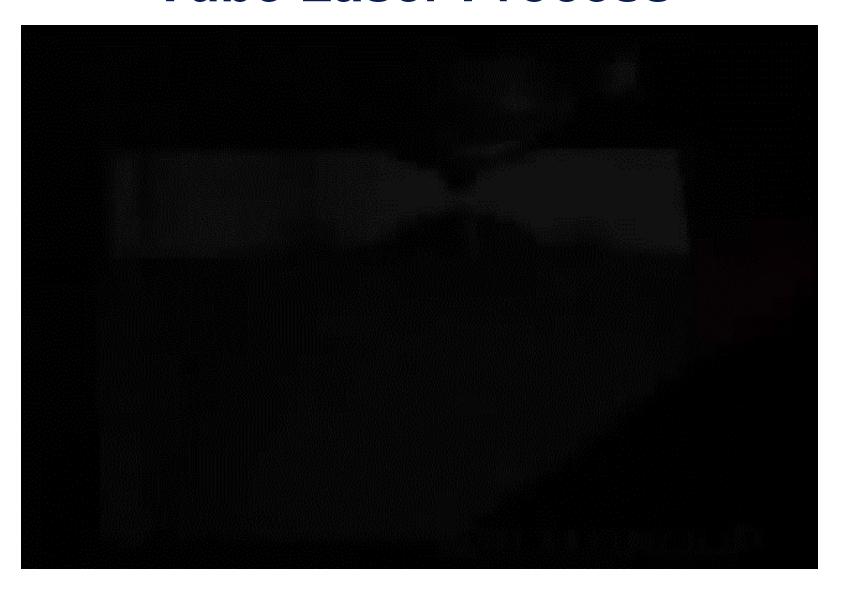
High Speed Wire Forming



Wire Form Examples



Tube Laser Process



Rectangular/Square Tube laser cut hand bending



Rectangular/Square Tube

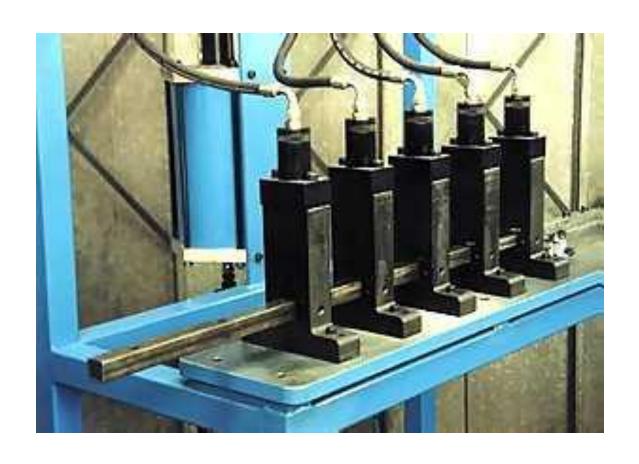
Laser Cut - Creative Weldless Connections







Punching Process Tube Punching



Punching Process Bar Punching



End Forming Processes

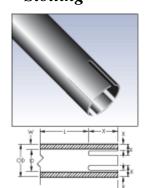
Reduction



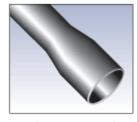
Flattening

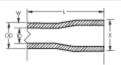


Slotting



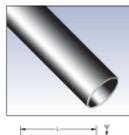
Expansion

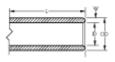




Forming

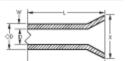






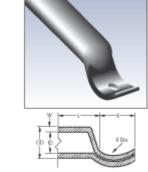
Flaring



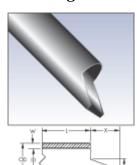


Flanging



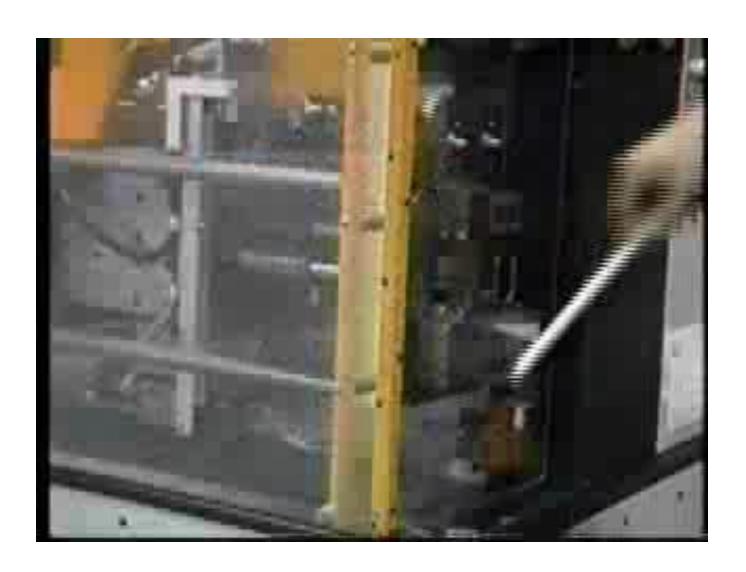








End Forming Video

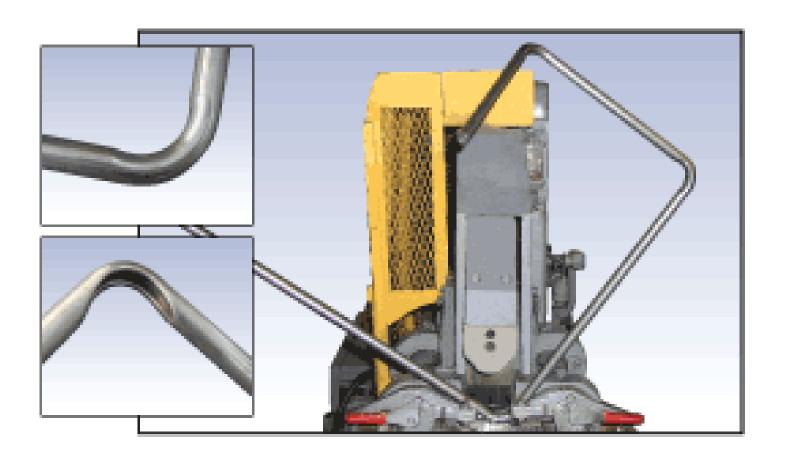


Circular Sawing Video Multiple Parts - Bundling



Tube/Bar Bending Processes

Compression/Ram Bending



Primary Metal Casting Processes

- 1. Die Casting
- 2. Sand Casting
- 3. Permanent Mold Casting
- 4. Investment Casting

Die Casting

A non-ferrous metal is injected into a metal mold cavity under high pressure

- Pressure is maintained during solidification, then mold is opened and part is removed, often by robotic manipulator
- Use of high pressure to force metal into die cavity achieves high production rates

<u>Die Casting</u> <u>Animation</u> <u>Video Clip</u>

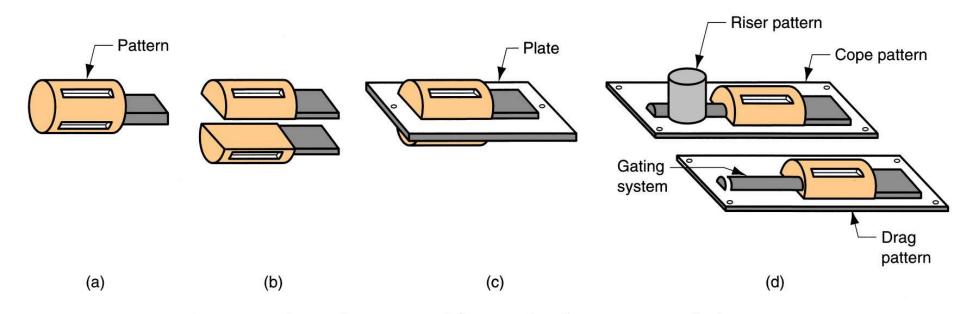


Sand Casting – Patterns required

Pattern – a model of the part, slightly enlarged to account for shrinkage and machining allowances

Types of patterns used in sand casting:

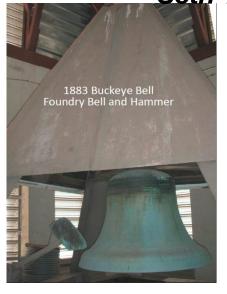
- (a) solid pattern, (b) split pattern, (c) match-plate pattern
- (d) cope and drag pattern

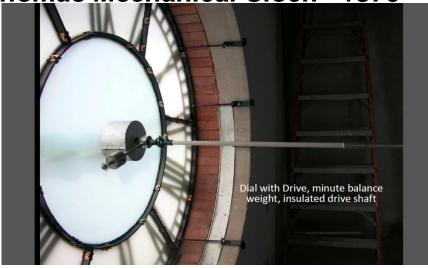


Urbana Courthouse Clock Tower Renovation - 2009



Seth Thomas Mechanical Clock - 1876







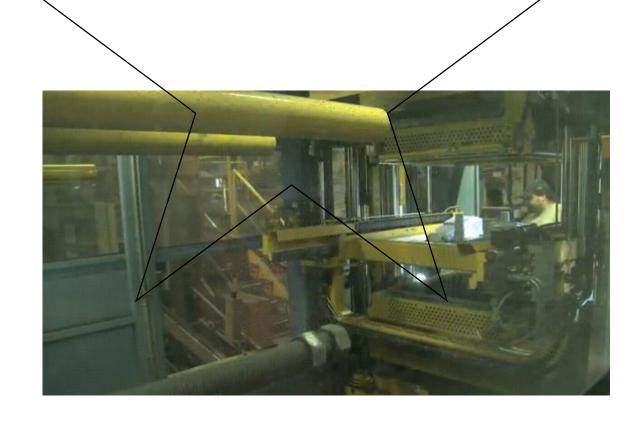


Restoration: 2002 - 2009

Horizontal Automatic Sand Casting

- Vertical or Horizontal Mold Making Machines
 - 200 to 600 parts/hr
 - Patterns and cores placed/in by robotic device

Horizontal Molding Machine video



Investment Casting (Lost Wax Process)

- A pattern made of wax is coated with a refractory material to make mold, after which wax is melted away prior to pouring molten metal
- "Investment" comes from a less familiar definition of "invest" - "to cover completely," which refers to coating of refractory material around wax pattern
- It is a precision casting process capable of producing castings of high accuracy and intricate detail

Lost Wax Video

Permanent Mold Casting







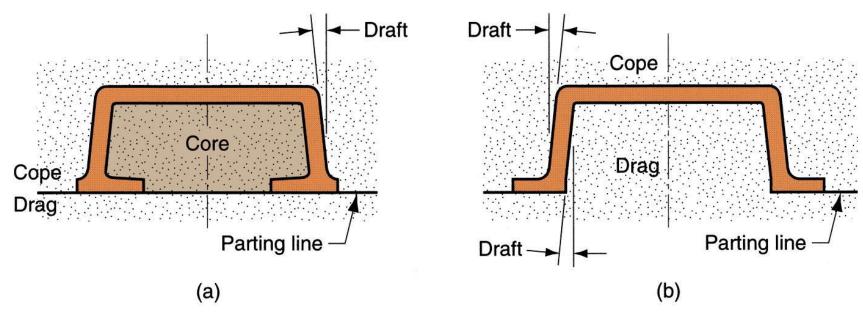


Product Design Considerations

- 1. Geometric simplicity that allows for shrinkage and reduces the need for cores.
- 2. Reduce sharp angles by rounding corners and reducing stress concentrations areas that may cause hot tearing and cracks.
- 3. Increase draft angles (interior and exterior). Minimums:
 - Draft = 1° for sand casting
 - Draft = 2° to 3° for permanent mold processes

Draft

Minor changes in part design can reduce need for coring



Design change to eliminate the need for using a core: (a) original design, and (b) redesign.

Product Design Considerations - Cont

4. Dimensional Tolerances and Surface Finish:

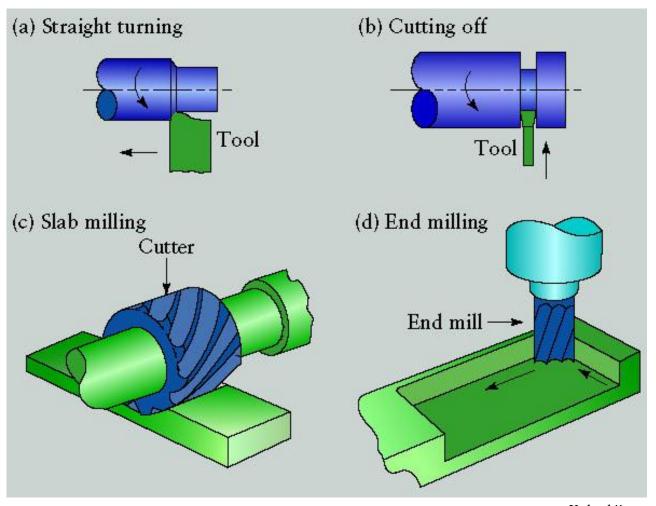
- Sand casting: poor dimensional accuracies and finish
- Die casting and investment casting: better dimensional accuracies and finish

5. Machining Allowances:

 Additional material, called the machining allowance, is left on the casting in those surfaces where machining is necessary

Introduction to Machining

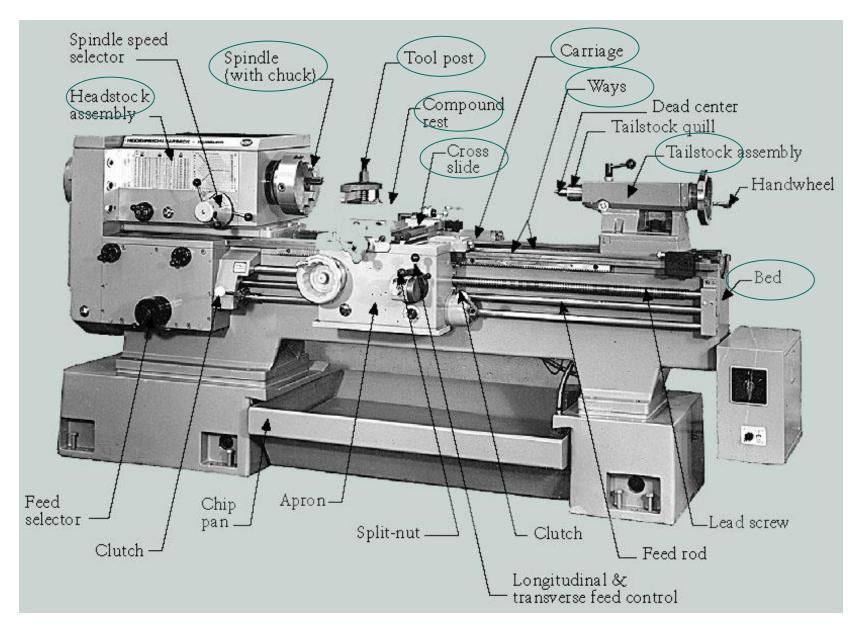
Common Machining Operations



Aka: Material Removal Processes

Kalpakjian

Parts of an "Engine" Lathe



Watchmaker's lathe



Turret Lathe



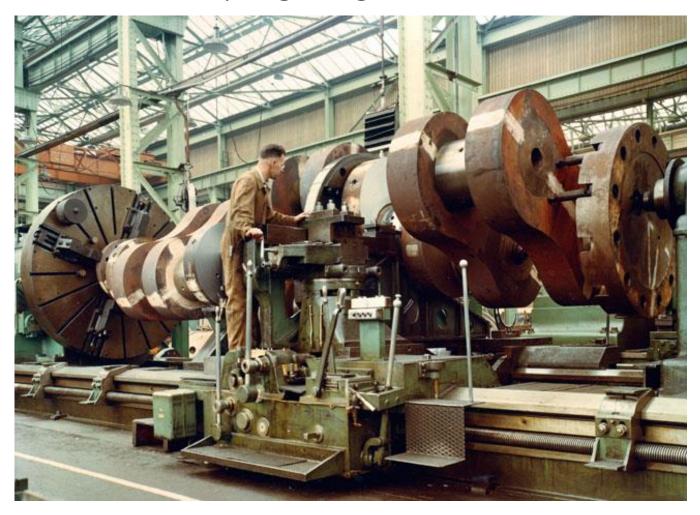
Typical "Engine" Lathe



Big "Engine" Lathe



Really Big "Engine" Lathes



www.practical machinist.com

CNC Lathe: aka "Turning Center"

(carriage is mounted toward back, "upside down")



www.machineryvalues.com

<u>CNC = Computer Numerical Control (features are machined to size and location by a computer)</u>

CNC MILL or "Machining Center"



Links:

<u>CNC machining engine block from solid</u>

<u>Milling an Impeller</u>