

Product Costing Guidelines

Integrated Product Development (IPD)

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Compiled by
William Lovejoy
Sebastian Fixson
Shaun Jackson

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1 Introduction

This document describes the economics of common manufacturing processes, and some design considerations and constraints for each. It contains a list of processes and the following information for each: description of the process, cost information, design guidelines, and sources for further information. The list of processes allows a selection from a large set of existing possibilities. If you decide to use a process not listed here, often one of the listed processes can serve as a baseline from which you can develop your own proposed costing data. If you develop your own cost models to estimate the cost of your product, your model should be validated by the instructors.

The design guidelines are meant to avoid stark mistakes. To master any particular manufacturing process obviously requires much more in-depth knowledge. However, this broad overview can suggest the choice of economical processes and help avoid unnecessarily costly product designs.

2 Required Costing Documents

The costing documents to be handed in with your fully functional prototype must include the following:

- a) Summary Excel page that shows for all parts in the product, no matter how small, its fixed tooling and variable manufacturing, procurement or assembly cost. The list should also indicate for each part where (what page number) to look in the costing documentation for detailed costing information. The final fixed and variable cost should be reported clearly in summary form on this spreadsheet.
- b) On the internal pages indicated on the summary page, justify the reported fixed and variable cost for each part or subassembly.

For sourced parts, this means justifying your costs with receipts or valid quotes (DO NOT abuse vendors, be honest about your intentions in all interactions with vendors).

For manufactured parts (this should be most of them) use these costing guidelines and clearly show your assumptions and calculations.

For assembly costs, show the sequence (a sketch is clear) of steps to assemble parts into subassemblies, and subassemblies into your finished product. Use the costing guidelines to cost out the steps.

Finishing operations. Provide the necessary buffing, painting, etc. activities and cost them out using these guidelines.

- c) Any additional documentation relevant to support the product cost estimate.

In practice, unclear or confusing documentation results in miscommunication, errors and rework. Therefore, the instructors will adjust your variable cost based on the accuracy, clarity and completeness of your costing documentation relative to those handed in by other teams.

3 Process Descriptions

3.1 Casting processes

3.1.1 Sand casting

a) Process description and potential materials

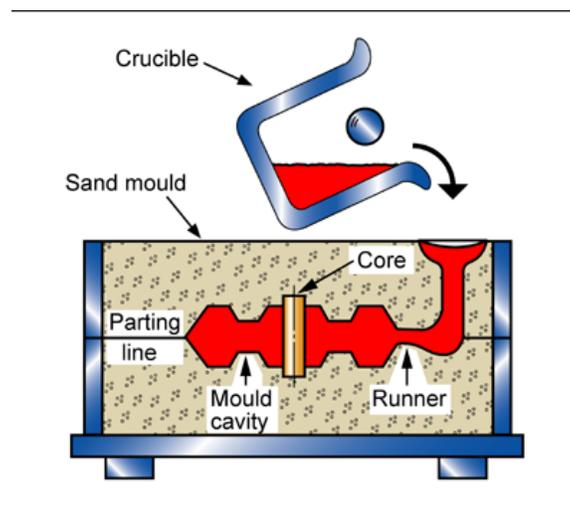
Process description

Sand casting can be used for just about any metal that can be melted. A sand mold is formed by packing sand around a wood or metal pattern which has the same shape as the part to be cast. The pattern, and the sand box that it is embedded in, are usually made in two halves that can be separated to remove the pattern once the sand is packed in, and holes are made for pouring molten metal in and for allowing gas to escape.

Metal is melted, poured into the holes to fill the mold, and it is left to cool. When the cast part has cooled, the box is opened and the part removed. The sand is disturbed when the part is removed, so that the set up operation must be repeated for each part. Hence, variable costs tend to be high for sand casting, and this method is usually used for large parts in low volumes that, because of their size, are not suitable for other processes.

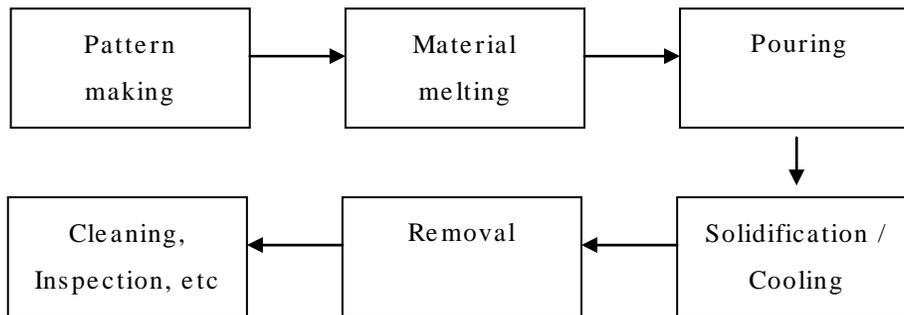
Sand castings tend to have a grainy surface with poor dimensional control. Most often castings are machined in post processing operations for smoothness and dimensional integrity.

Process schematic



<Source: CES (Cambridge Engineering Selector) Ver. 4.5>

Process flow chart

**Material**

Used for a wide range of metal alloys including aluminum and copper alloys, cast irons and steels. In principle, any non-reactive, non-refractory metal ($T_m < 2000K$) can be used

b) Costing information*Fixed cost:*

Machine n patterns. The cost of a set of identical pattern impressions is given by

$$C_{pi} = R_t (0.313N_{sp}^{1.27} + 0.085A_p^{1.2})n^{0.7}$$

where,

R_t = toolmaking (pattern shop) rate, assume this to be 40 \$/h

N_{sp} = number of surface patches (see below)

A_p = projected area of impressions, cm^2 ($in^2 = 6.452 cm^2$)

n = number of identical impressions

N_{sp} (the number of surface “patches”) is the number of continuous areas on the part, that can be machined without lifting the tool. For example, a simple disk will have three: the top surface, the bottom surface, and the edge. A disk with a hole in the middle will have four patches.

Variable costs per pour:

The inputs to the costing model are:

N = number of cavities you will fill per cycle (less than or equal to 100).

n = number of patterns that you manufacture (less than or equal to N).

V = volume of the part to be cast, in in^3 .

A = floor area taken up by the box holding the sand and the part. Assume a rectangular box that has 2” clearance on all sides from the pattern.

ρ = Material density (lb/in^3)

m = dollar cost of material (\$/lb)

Materials cost per pour: The material cost for N parts in a pour will $1.03NmpV$ dollars. This assumes 2% waste.

Set up N cavities: Charge yourself N/n dollars.

Ladle the molten metal: Charge yourself .03N dollars.

Allow to cool: Charge yourself .008NA dollars

Variable cost per part: Divide the variable cost per pour by N.

Example: You want to make a part out of medium cast iron which costs \$.73/lb and has a density of .258 lb/in³. The part has a volume of 8 cubic inches and a projected area of the sand box equal to 36 square inches. Pattern has 1 surface patch. You decide to make 10 parts per pour (N=10). You machine one pattern (n=1) and intend to set up the sand boxes sequentially using your one pattern. The sand casting costs for this part will be as follows:

$$\text{Fixed cost: } (40)(0.313 \cdot 1 + 0.085 \cdot (36 \cdot 6.452)^{1.2}) \cdot 1^{0.7} = \$2,360$$

Variable costs per pour of 10 parts:

$$\text{Materials: } (1.02)(10)(.73)(.258)(8) = \$15.37.$$

$$\text{Set up: } 10/1 = \$10.$$

$$\text{Ladling: } (.03)(10) = \$0.30.$$

$$\text{Cooling: } (.008)(10)(36) = \$2.88.$$

$$\text{Total per pour} = 15.37 + 10. + .30 + 2.88 = \$28.55.$$

$$\text{Total per part} = 28.55/10 = \$2.85.$$

So for this part you would report a fixed tooling cost of \$2,360 and a variable cost per part of \$2.85. If you wanted a nice surface finish or if some aspects of the part had to conform to tight tolerances, you would have to add the cost of some post-processing machining steps to each part.

If you decided to machine 10 patterns (so n = 10), you would increase the fixed cost to \$11,828, but the variable cost would be reduced by nine dollars per pour (N/1 - N/n = 10 - 1 = 9), and would equal \$19.55 per pour or \$1.96 per part.

In this example, if you were making 100,000 parts the optimal number of pattern made would be 11 (or, approximately 10). The figures for various N are as follows.

F (Fixed cost / pattern) =		\$2,360		
T (Total production volume) =		100,000		
n* (Optimal pattern made) =		$(T/0.7F)^{(1/1.7)}$		
		= 11		
N	n* (n* <= N)	Fixed	Variable	Total cost at 100,000 parts

1	1	2,360	2.855	287,860
2	2	3,834	2.355	239,334
3	3	5,092	2.188	223,925
4	4	6,228	2.105	216,728
5	5	7,281	2.055	212,781
6	6	8,272	2.022	210,439
7	7	9,215	1.998	209,000
8	8	10,118	1.980	208,118
9	9	10,987	1.966	207,598
10	10	11,828	1.955	207,328
11	11	12,644	1.946	207,235
20	11	11,828	1.955	207,328

n* = optimal number of patterns to manufacture given that you want to produce 100,000 parts.

c) Design guideline

Bosses, undercuts, inserts and hollow sections are all practical. Shapes are frequently solid but complex internal shapes can be made using cores. Sand casting is not the best way to go for high volume parts, since the variable costs are usually high.

d) Data Sources / Sources for further Information

CES (Cambridge Engineering Selector) Ver. 4.5, Software

Geoffrey Boothroyd, Peter Dewhurst, Winston Knight (2002). Product Design for Manufacture and Assembly. New York, Marcel Dekker.

Robert C. Creese, M. Adithan, B.S. Pabla. (1992). Estimating and Costing for the Metal Manufacturing Industries. New York, Marcel Dekker.

3.1.2 Investment casting

a) **Process description and potential materials**

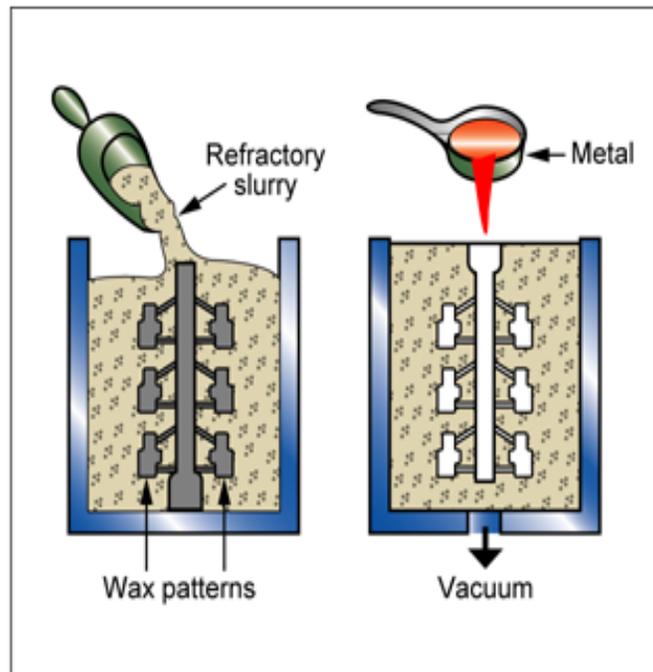
Process description

In investment casting, wax patterns are made by injection molding into a metal die and then assembled on a tree with feeding and gating systems. The wax pattern is dipped into a refractory slurry, then covered in a refractory stucco, and allowed to dry for a number of hours. This procedure is repeated a number of times, usually until about 8 coats of refractory have been achieved. This is the ceramic investment shell. The wax is then melted out - preferably in a steam autoclave. The ceramic shell is fired to around 1000C and then the molten metal is cast into it. Air pressure, vacuum or centrifugal pressure can be used to ensure complete filling of the mold when complex, thin sections are involved. The mold is broken up to remove the castings.

The process is suitable for most metals with melting points below 2500K. Because the wax pattern is melted out, shapes can be very complex with contours, undercuts, bosses, recesses, etc.

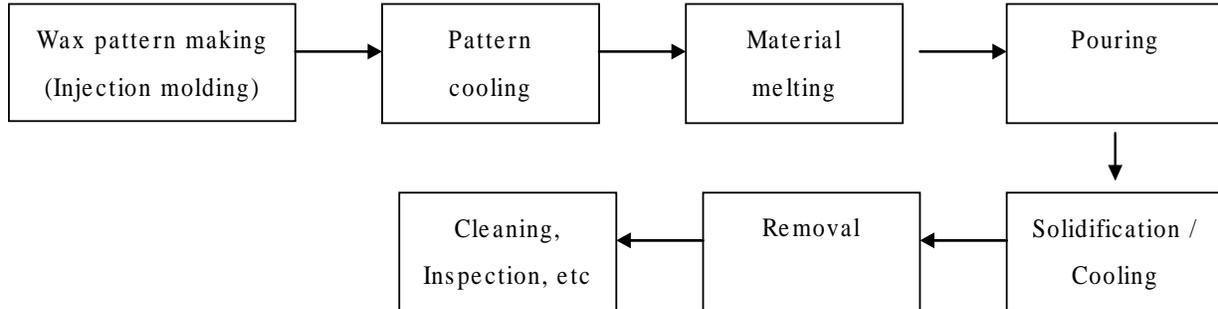
The process requires precision tooling for making the wax patterns and involves many steps which are time consuming, and therefore, it is expensive. The process is also known as the Lost Wax Process.

Process schematic



<Source: CES (Cambridge Engineering Selector) Ver. 4.5>

Process flow chart

*Material*

Suitable for a wide range of ferrous, non-ferrous and special alloys.

b) Costing information

Begin by understanding the sand casting costing method, and then make the following adjustments.

Fixed cost:

Cost out the tool that makes the wax patterns as if you were injection molding the pattern, using the injection molding guideline. Take the fixed tooling cost from the injection molding module. Ignore the variable costs from that module.

Variable costs:

The wax cannot be reused, so $n = N$.

Add \$.25/part for the wax cooling time and handling. Everything else is as in the sand casting costing guidelines.

c) Design guidelines

Very complex shapes with contours, undercuts, bosses, recesses, etc. Best for small 3-D shapes. You can get better surface finishes and hold tighter tolerances with investment casting, so that you may be able to eliminate post-processing operations.

d) Data Sources / Sources for further Information

CES (Cambridge Engineering Selector) Ver. 4.5, Software

Geoffrey Boothroyd, Peter Dewhurst, Winston Knight (2002). Product Design for Manufacture and Assembly. New York, Marcel Dekker.

Robert C. Creese, M. Adithan, B.S. Pabla. (1992). Estimating and Costing for the Metal Manufacturing Industries. New York, Marcel Dekker.

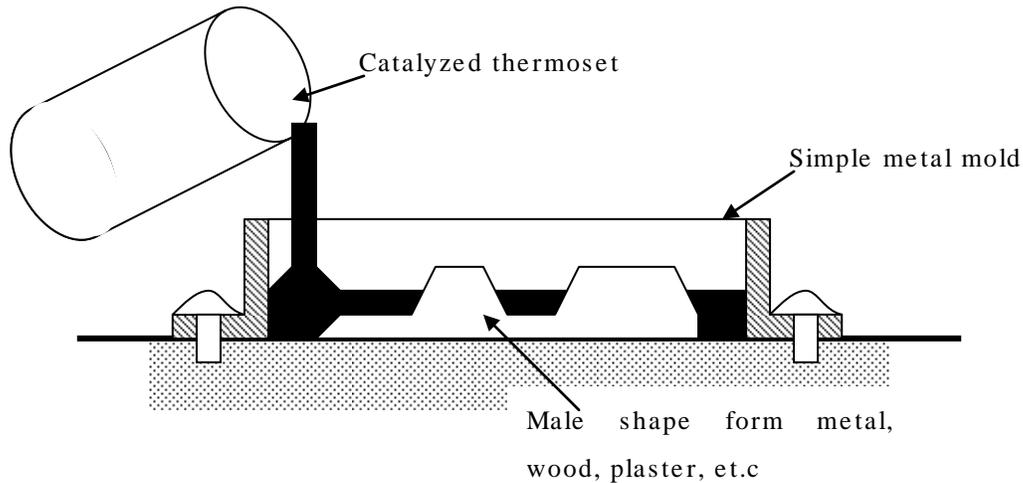
3.1.3 Thermoset casting

a) Process description and potential materials

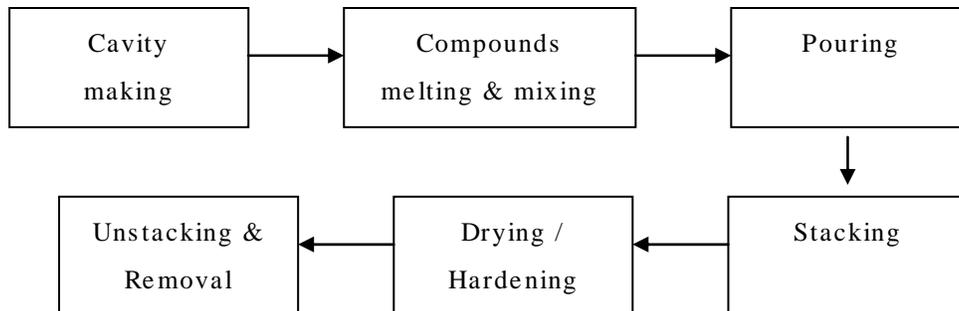
Process description

Thermosets are plastics that are formed by mixing two compounds and letting them harden. If the plastic is poured into a mold prior to hardening, then the resulting solid will take the shape of the mold cavity. Thermosets are not recyclable, so that scrap is wasted instead of being cut up and re-used in the manufacturing process. The processing advantage of thermosets is that the molds can be stacked while they harden, so that the time spent in hardening is not time taken on an expensive machine (as in the cooling time in injection molding), but time taken stacked on the floor somewhere. Hence, this is a good process to consider for parts that are very thick and would require long cooling times if injection molded.

Process schematic



Process flow chart



Material

Thermoset plastics

b) Costing information

The costs associated with thermoset casting involve:

- 1) Creation of the mold cavity, and cover if necessary.
- 2) Material costs.
- 3) Pouring the compounds.
- 4) Stacking the molds for drying.
- 5) Usage of storage volume while the plastic hardens.
- 6) Unstacking the molds.

We will cost out the materials at the volume required plus 3% wastage.

We will cost out the creation of the mold cavities using the IPD machining guidelines.

The opportunity cost for storage space will be presumed to be \$5 per square foot for each cooling (setting) cycle. Assume at least a 10-cavity tool, and determine the flat surface area per tool by laying out the cavities and leaving a 2" buffer between parts and between the parts and the sides of the tool. Assume that you can stack tools 10 high. So, if you make one tool with 10-cavities it will cost $\$(5/10)xA = \$.5A$ in setting time per cavity (part). If you make 2 tools the cost per cavity is $\$(5/20)xA = \$.25A$. If you make 10 such tools and stack them it will still take just A square feet of floor area, and cost you $\$(5/100)xA = \$.05A$ in setting time per cavity (part). In general if you build N 10-cavity tools, your setting time cost will be $(5/(10N))xA = A/(2N)$ \$ per part.

We will assume that the time to mix a batch for an entire production run is, on a per-cavity basis, negligible (for high volume production, you could mix one huge batch and drive this cost per part practically to zero). The variable labor costs come from pouring the compound into the cavities. Assume this takes 15 seconds per pour, and cost out this time at \$45/hour. Hence, the labor cost per cavity (part) will \$.1875.

In summary your costs will be as follows.

Fixed tooling cost:

Cost out tooling cost using tooling cost in machining guideline. If you make N 10-cavity tools in total and the cost per cavity is C \$/cavity, then your fixed cost = 10NC \$.

Variable costs per part:

Cost = $1.03M + A/(2N) + .1875$ \$/part.

Where

N = number of 10-cavity molds you manufacture

M = material cost for the volume of material used in each part (cavity) (\$).

A= floor area taken up by a single 10-cavity mold (ft²).

Example

A part with volume 9 cubic inches will be made from a thermoset plastic. 9 cubic inches of this plastic costs \$.74 (= M). The material cost per part will be $1.03(.74) = \$.762$.

Cost out the creation of one 10-cavity tool using machining guidelines. Suppose the material removal rate is $1.5 \text{ in}^3/\text{min}$ so each cavity will take $9/1.5 = 6 \text{ min}$ or $.1 \text{ hours}$ which at $\$30/\text{hour}$ costs $\$3$ (see the machining costing guidelines). So, the fixed costs will be $30N$ where N is the number of 10-cavity molds made.

Assume a single 10-cavity mold takes up 4 square feet ($A = 4$) of floor space.

Hence, the total costs to report for this part will be:

Fixed cost = $30N$

Variable cost = $.762 + .1875 + 4/(2N) \text{ \$/part}$

So, there is a fixed versus variable cost tradeoff in how many 10-cavity tools to make.

c) Design guidelines

It is important to ensure that thorough mixing take place to maximize performance.

d) Data Sources / Sources for further Information

Dominick Rosato, Donald Rosato, Matthew Rosato, (2004), Plastic Product Material & Process Selection Handbook, Oxford, Elsevier

Dominick Rosato (1997), Plastics Processing Data Handbook, 2nd edition, Cambridge, Cahmpman & Hall

3.14 Die casting

Die casting is essentially the same process as injection molding, except that metals are cast rather than plastics. See the injection molding section for a general description of the process. The IPD die casting cost model uses the same inputs as injection molding, and costs out tooling in the same fashion. The only significant difference is that cooling times in die casting are less driven by maximal wall thickness, because of the high conductivity of most metals. Also, for the same reason, some care must be taken to keep the part from cooling too rapidly, preventing a complete pour from being completed successfully.

The model for die casting is the same as for injection molding except the cooling time is computed as a linear (rather than quadratic) function of maximal part wall thickness:

$$T_c = \beta h_{\max} \text{ (seconds)}$$

Where the appropriate β for different metals is

Metal	β
Zinc alloys	.4
Aluminum alloys	.47
Copper alloys	.63
Magnesium alloys	.31

SUMMARY (see detailed instructions in injection molding section for these inputs)

The fixed tooling cost is the base cost plus the mold machining cost where

$$\text{Base cost} = 1000 + 10.58 \times A \times (d+6)^{.4} \text{ (\$)}$$

$$\text{Mold machining cost} = 75 A^{.5} + 2700*(.08 + .04*SP)^{1.27} + 300 + 120*A^{(1.2)} \text{ (\$)}$$

A = projected area (in²)

d = part depth (in)

SP = number of surface patches on the part

The variable cost per part is the materials cost plus the cooling time cost (at \$60/hour for the machine) which are as follows:

$$\text{Materials} = 1.03*(\text{cost of material for one shot}) \text{ (\$/shot)}$$

$$\text{Machine cooling time cost} = \beta h_{\max}/60 \text{ (\$/shot)}$$

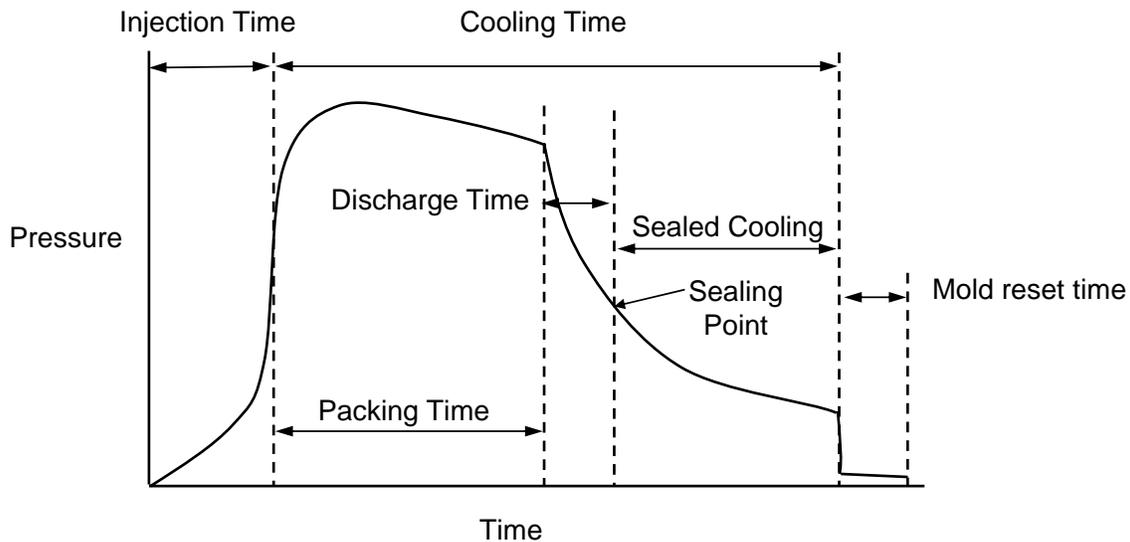
If you make more than one part per shot, input the projected area and the volume and maximal wall thickness for the entire part family.

Data Sources / Sources for further Information

Boothroyd, G, P. Dewhurst and W. Knight. Product Design for Manufacture and Assembly. Dekker, 1994.

and fine detail reproduces well. Decorative labels can be molded onto the surface of the component (see In-mould Decoration). The only finishing operation is the removal of the sprue.

Injection Molding Cycle



Materials

Thermoplastics, thermosets and elastomers can all be injection molded. Co-injection allows molding of components with different materials, colors and features. Injection foam molding allows economical production of large molded components by using inert gas or chemical blowing agents to make components that have a solid skin and a cellular inner structure.

b) Costing information

Injection molding requires relative expensive tooling. For this reason, injection molding is suited for large production volumes. Production rate can be high particularly for small moldings. Multi-cavity molds are often used. Prototype moldings can be made using single cavity molds of cheaper materials.

The costs of injection molding are mainly driven by the materials cost, the required equipment (press) the cycle time on the machine, and the required (and dedicated) tooling.

Equipment Size

The equipment size is determined by the clamp force which is determined by the part size and the number of cavities. However, we are not going to model the different machine sizes and costs explicitly in IPD.

Molding Cycle Time

The molding cycle time on the machine consists of the injection time (which depends on the shot size and machine power, but is usually small: 1-2 secs) and the cooling time (this usually

dominates). The cooling time can be approximated as follows, which is largely driven by the square of the maximal wall thickness:

Cooling Time

$$t_c = \frac{h_{\max}^2}{\pi\alpha} \log_e \frac{4(T_i - T_m)}{\pi(T_x - T_m)} s$$

h_{\max} = maximum wall thickness

T_x = recommended part ejection temperature, C

T_m = recommended mold temperature temperature, C

T_i = polymer injection temperature, C

alpha = thermal diffusivity coefficient, mm²/s

However, we will use a simplified model. See the variable cost section below.

Mold Cost Estimation

The mold cost consists of the cost of the mold base, and the cost of the cavity and core fabrication. We will approximate these costs using simplified versions of the logic in Bothroyd, Dewhurst and Knight (2002)

Mold base cost

The mold base cost is the cost of basic material that will be machined to make the part. This depends on the projected area of your part(s) and the depth needed. To get these numbers, draw your part within square, as if you are looking down on the tool seeing is length and width, but not depth. That is, sketch the outlines of the parts and draw a square around it (or them, if you are making multiple parts with one shot). Leave 2" between any part and any other part, and any part and the edge of the square. This 2" leeway is to leave room for runners, cooling channels, and other things that a tool requires. So, for example, if you are going to make 5 parts in one shot you will have 5 cavities all of which are at least 2" from each other and 2" from the edge of the circumscribing square. Define

A = projected area (in²) = the area of the square enclosing the parts, including 2" boundary on all sides.

d = part depth (in), this comes from measuring the depth of the actual part, as it will lie in the box. There is no need to add a boundary to this, just measure the part itself.

The mold base cost will be

$$\text{Cost} = 1000 + 10.58 A (d+6)^{.4} \$$$

Cavity and Core Manufacturing Costs

The following activities during mold manufacturing are major cost drivers:

- Cavity milling
- Deep hole drilling for cooling channels

- Side action
- Ejector system

Boothroyd, Dewhurst and Knight cite a number of studies that estimate the mold costs as a function of various inputs. For example, the number of ejector pins needed in a tool is roughly equal to the square root of the projected area. And, a rough estimate is 2.5 manufacturing hours per ejector pin for the ejector system. Costing out this labor at \$30/hour yields a cost for the ejector system of

$$(30)(2.5)(A)^{.5} = 75 A^{.5} (\$)$$

where A = projected area of the box described above.

The complexity of the part is determined by its number of “surface patches,” which are continuous surfaces that a tool can traverse without lifting. This determines the bulk of the machining costs, so count these carefully. The machining cost will be

$$2700(.08 + .02 SP)^{1.27} (\$)$$

where SP = number of surface patches.

In addition to its complexity, the size of the mold affects the machining costs by adding the term

$$300 + 120 A^{1.2} (\$)$$

to the tool cost. So, in summary, the cost to manufacture the mold is

$$75 A^{.5} + 2700*(.08 + .04*SP)^{1.27} + 300 + 120*A^{(1.2)} (\$)$$

A = projected area (in²)

SP = number of surface patches.

Summary of fixed cost for injection molding

The total fixed cost for injection molding will be the base cost plus the machining cost, where

$$\text{Base cost} = 1000 + 10.58 \times A \times (d+6)^{(.4)} (\$)$$

$$\text{Mold machining cost} = 75 A^{.5} + 2700*(.08 + .04*SP)^{1.27} + 300 + 120*A^{(1.2)} (\$)$$

A = projected area (in²)

d = part depth (in)

SP = number of surface patches on the part

Variable costs

The variable cost per part produced is the material cost plus the machine time cost. The machine time cost is driven by cooling time, which in turn depends on the square of the maximal wall thickness. Here are the models to use:

Materials

Compute the volume of material in each shot (the sum of the part volumes in each shot, if just one part is made per shot it is the part volume) and multiply 1.03 to account for scrap rate and runner losses.

Machine time

The heat transfer equation above can be approximated in simplified form to estimate the cooling time (in seconds) as

$$131 h_{max}^2/\alpha \text{ (sec)}$$

where

α = thermal diffusivity from the chart below (mm^2/sec)

h_{max} = maximal wall thickness (inches)

We charge \$60/hour machine time, so the cost will be

$$2.18 h_{max}^2/\alpha \text{ (\$/shot)}$$

Summary of injection molding variable cost

Materials = $1.03 \times (\text{cost of material for one shot})$ (\$/shot)

Machine time cost = $2.18 h_{max}^2/\alpha$ (\$/shot)

Where

α = thermal diffusivity from chart (in mm^2/sec)

h_{max} = max wall thickness (inches)

You can get thermal diffusivities for some common injection molded materials from the following table from Boothroyd, Dewhurst and Knight as follows:

Injection molding data
(Data from BDK 2002, p. 358)

Thermoplastic	Specific gravity	Thermal diffusivity (mm ² /s)	Injection temp (C)	Mold temp (C)	Ejection temp (C)	Injection pressure (bars)	Approx cost (\$/kg)
High-density polyethylene	0.95	0.11	232	27	52	965	0.9
High-impact polystyrene	1.59	0.09	218	27	77	965	1.12
Acrylonitrile-butadien-styrene (ABS)	1.05	0.13	260	54	82	1000	2.93
Acetal (homopolymer)	1.42	0.09	216	93	129	1172	3.01
Polyamide (6/6 nylon)	1.13	0.1	291	91	129	1103	4
Polycarbonate	1.2	0.13	302	91	127	1172	4.36
Polycarbonate (30% glass)	1.43	0.13	329	102	141	1310	5.54
Modified polyphenylene oxide (PPO)	1.06	0.12	232	82	102	1034	2.75
Modified PPO (30% glass)	1.27	0.14	232	91	121	1034	4.84
Polypropylene (40% talc)	1.22	0.08	218	38	88	965	1.17
Polyester terephthalate (30% glass)	1.56	0.17	293	104	143	1172	3.74

For materials not on this list, you will have to find and document its material properties.

SUMMARY

The fixed tooling cost is the base cost plus the mold machining cost where

$$\text{Base cost} = 1000 + 10.58 \times A \times (d+6)^{.4} \text{ (\$)}$$

$$\text{Mold machining cost} = 75 A^{.5} + 2700 \times (.08 + .04 \times \text{SP})^{1.27} + 300 + 120 \times A^{(1.2)} \text{ (\$)}$$

A = projected area (in²)

d = part depth (in)

SP = number of surface patches on the part

The variable cost per part is the materials cost plus the cooling time cost where

$$\text{Materials} = 1.03 \times (\text{cost of material for one shot}) \text{ (\$/shot)}$$

$$\text{Machine cooling time cost} = 2.18 \text{ hmax}^2 / \alpha \text{ (\$/shot)}$$

If you make n parts on each shot, the variable cost per part is the (\$/shot) divided by n.

c) Design Guidelines

Most thermoplastics can be injection molded, although those with high melting temperatures (e.g. PTFE) are difficult. Thermoplastic based composites (short fiber and particulate filled) can be processed providing the filler-loading is not too large. Large changes in section area are not recommended. Small re-entrant angles and complex shapes are possible, though some features (e.g. undercuts, screw threads, inserts) may result in increased tooling costs. The process may also be used with thermosets and elastomers. The most common equipment for molding thermoplastics is the reciprocating screw machine, shown schematically in the figure. Polymer granules are fed into a spiral press where they mix and soften to a dough-like consistency that

can be forced through one or more channels ('sprues') into the die. The polymer solidifies under pressure and the component is then ejected.

d) Data Sources / Sources for further Information

CES (Cambridge Engineering Selector) Ver. 4.5, Software

Geoffrey Boothroyd, Peter Dewhurst, Winston Knight (2002). Product Design for Manufacture and Assembly. New York, Marcel Dekker.

3.2.2 Blow molding (Extrusion)

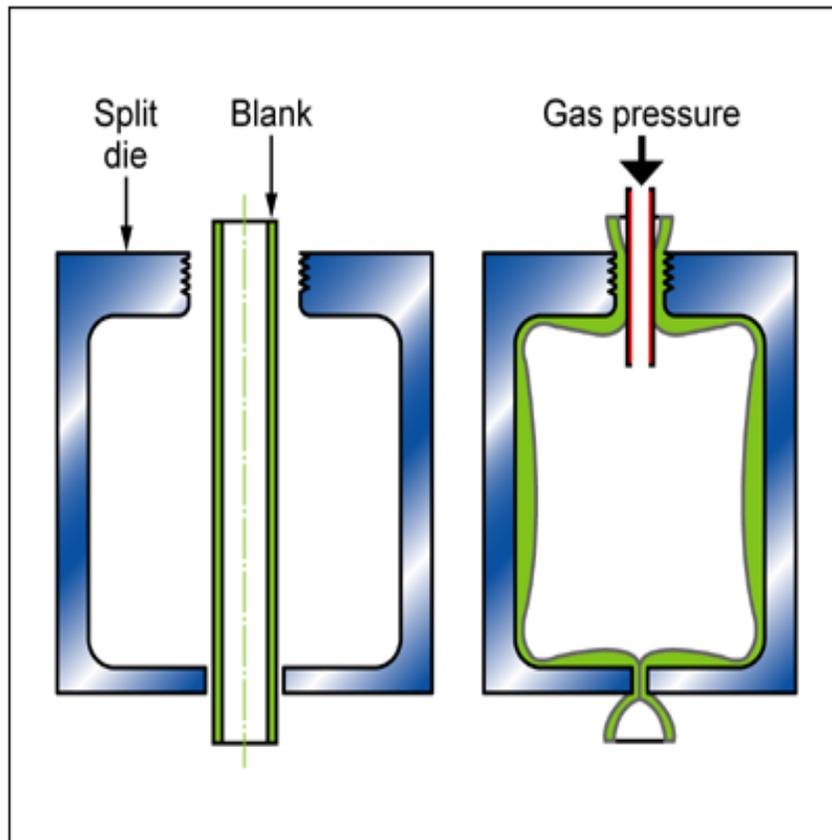
a) Process description and potential materials

Process description

Extrusion blow-molding is a good process for hollow thermoplastic objects (especially bottles and containers). The process begins just like an extrusion process, in which a thin tube is extruded into the middle of a cavity. Then, air is blown into the tube forcing it to expand against the walls of the cavity. The outside wall of the part takes the shape of the cavity wall.

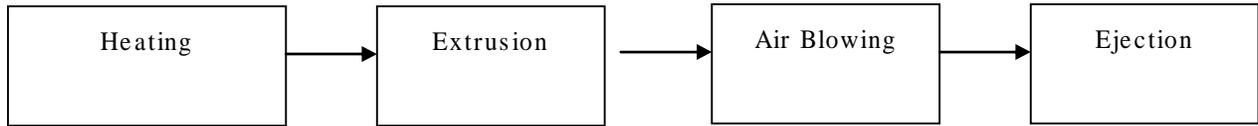
The part should have radial symmetry, and be relatively smooth. The simplicity of shape is what allows this process to work. Shapes more complicated than plastic pop bottles or baseball bats will be considered too complex for blow molding. See the instructors for an appraisal of the part.

Process schematic



<Source: CES (Cambridge Engineering Selector) Ver. 4.5>

Process flow chart

*Material*

Thermoplastics commonly used include: HDPE, LDPE, PP, ABS and uPVC.

b) Costing information

If you can blow mold the part, we will use the following cost model. The major differences (we will assume) between extrusion blow molding and regular extrusion are:

- 1) The need for the forced air mechanism (increasing machine costs).
- 2) The cooling time.
- 3) The control for wall thickness in case the part has different diameters (For example, consider a cone. The wider portion would have to begin with more material than the narrow portion and this would have to be controlled in the extruding process).
- 4) There is no need for a cutoff operation.

Hence, our costs can be computed as follows.

Costing guideline:

- Compute the die cost and the unit cost using the extrusion guidelines.
- Add to the die cost \$700 times the difference between the maximal radial diameter and the minimal radial diameter (in inches).
- Compute the machine time costs from the injection molding costing guideline model as an approximation.

Example:

Suppose you wanted to cost out a simple cone that is 5" tall, has a narrow diameter of 1" and a maximal diameter of 3", and has wall thickness of 1/8". You want to blow mold this part from high density polyethylene. The costs would be computed as follows.

Basic extrusion costs: A rectangle circumscribing the part would be 3" on a side, or 9 square inches in area. Hence, the die cost is
 $\$500 + 500(1) + 3(9) = \1027 .

Note that a blow molding die will always have a center cavity, and so $H=1$.

The per unit cost in the basic extrusion model is just the material cost, which is the volume used costed out at the extrusion cost model. The volume of plastic in this part is 3.93 in³ for the sides of the cone and .98 in³ for the two ends. So the total volume of plastic is 4.91 in³. Injection molding guideline gives us material cost of \$0.9/kg (= \$0.41/lb) and the specific gravity of .95.

This means that this material weighs .95 times as much as a similar volume of water. Multiply the specific gravity by .036 to get the lb/in³ for any material.

In this case, we get $(.95)(.036) = .0342$ lb/in³ which at 4.91 in³ volume is .168 lb per part, or $.168(.41) = .0688$ or \$.07/part.

This means that the piece part cost from the basic extrusion model is \$.07. I have assumed no difference in wall thickness, which is constant at 1/8”.

Adjustments for extrusion blow molding: Add \$700 times (3-1=2), or \$1400 to the tool cost. The machine time cost for a part of this configuration is computed using the injection molding costing guideline and

Material = high-density polyethylene

Weight = $(4.91)(0.95)(0.036)$ lb = 0.168lb = 76g

Volume = 4.91 in³

Maximum wall thickness = 1/8 in

Projected area = 7.07 in²

Part depth = 5 in

Number of surface patches inside = 1

Number of surface patches outside = 1

From the injection molding costing guideline, the machine time cost per part is \$.31.

So, the cost for extrusion blow molding for this part is:

Fixed tooling cost: $\$1027 + \$1400 = \$2427$

Variable cost per piece: $.07 + .31 = \$.38$

Note that if you wanted a cone without ends, you would have to cut these off as a secondary operation.

c) Design guidelines

Primarily used for bottles and containers - from small bottles to large (10000L) oil storage tanks. Useful for larger containers and irregular shapes e.g. detergent bottles, drums, tanks, toys (balls, baseball bats, etc.). Used for thin-walled hollow or tubular articles with small openings (e.g. bottles). Irregular shapes are possible.

The part should have radial symmetry, and be relatively smooth. The simplicity of shape is what allows this process to work. Shapes more complicated than plastic pop bottles or baseball bats will be considered too complex for blow molding. See the instructors for an appraisal of the part.

Limited level of reinforcement possible for composite materials (i.e. particulate and short fibers)

The wall thickness should be as uniform as possible to ensure more rapid molding cycles and to avoid distortion.

d) Data Sources / Sources for further Information

CES (Cambridge Engineering Selector) Ver. 4.5, Software

Geoffrey Boothroyd, Peter Dewhurst, Winston Knight (2002). Product Design for Manufacture and Assembly. New York, Marcel Dekker.

Dominick Rosato, Donald Rosato, Matthew Rosato, (2004), Plastic Product Material & Process Selection Handbook, Oxford, Elsevier

3.2.3 Compression molding

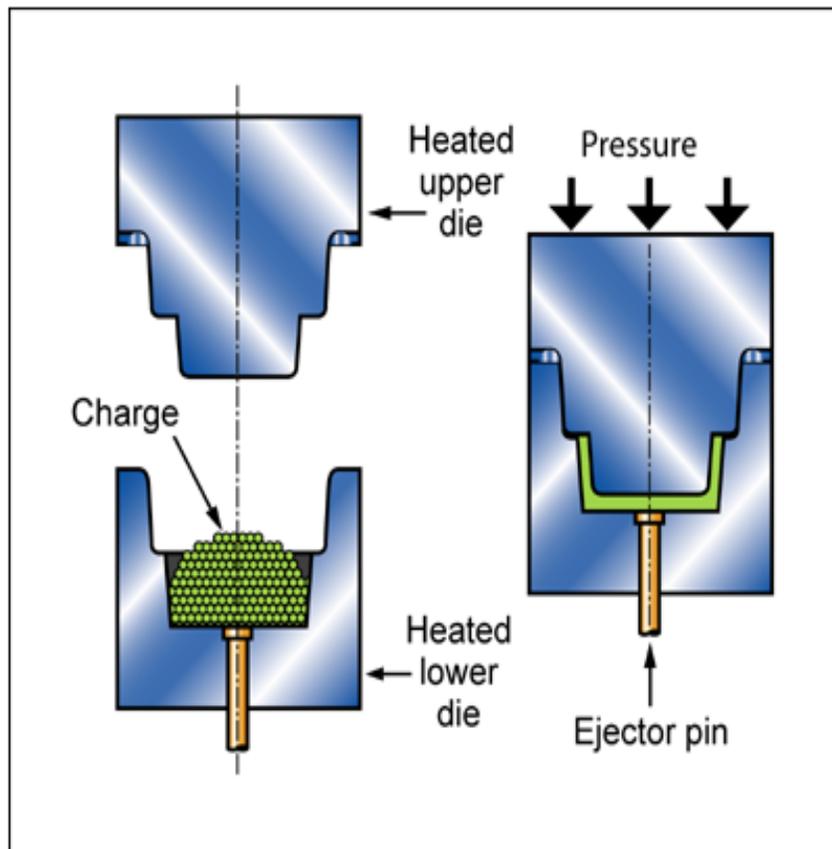
a) **Process description and potential materials**

Process description

Compression molding is similar to injection molding, except the machine is somewhat simpler. In compression molding, a slug of material, called a charge, is placed in a heated cavity where it softens. The mold is then closed forcing the plastic to take the shape of the cavity. Cooling times will depend on the maximal wall thickness, and range from about 20 seconds for small, thin-walled parts to several hours for very large, thick parts. The basic trade-off is to trade lower tooling costs for longer cycle times on cheaper machines. Also, the cavity must be fairly simple in shape so that the plastic will flow nicely under the ram pressure. There is no material lost in runner systems. We will assume a modest labor charge for placing the charge in the cavity. This will add very little to the variable cost of each part.

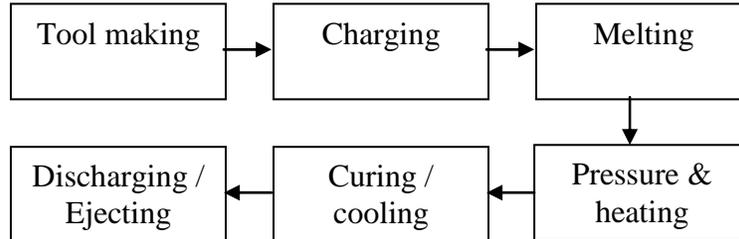
Thus, compression molding is a good choice for plastic parts with very simple shapes.

Process schematic



<Source: CES (Cambridge Engineering Selector) Ver. 4.5>

Process flow

*Material*

Mainly used with thermosetting plastics. However, elastomers and thermoplastics may also be processed.

b) Costing information

To cost these out in IPD, first make sure that your shape is very simple (half-spheres, cones, etc. that will easily fill under ram pressure). Cost out your part using the injection molding module. Then, adjust the costs as follows.

Tooling cost: Use 1/2 the basic injection molding cost guideline.

Material cost: Use the material costs per part from the injection molding cost guideline, as there is no lost material in runners in a compression mold.

Machine time: Use the injection molding machine time cost unadjusted. If we assume that the machine cost is 1/2 that of an injection molding machine, but the cooling time is twice as long, then the total variable cost for machine time remains constant.

Example calculation: compression molding for flat washer in ABS plastic.

Let's suppose injection molding cost guideline gives:

Total tooling cost: \$8,657.

Material cost/part with basic mold: \$.23

Machine time cost/part with basic mold: \$0.22

Hence, the relevant costs for compression molding are:

Tooling cost: \$4328.5

Material cost/part: \$.23

Machine time cost/part: \$.22

Total piece part variable cost: \$.55

Note that compression molding will always save fixed costs, so that compression molding is usually a better choice for simple part shapes. Hence, if you have a simple part shape that is amenable to a simple cavity and ram molding process, you will want to consider this process.

Note that you will still be penalized for very long cooling times, and this will still be driven by maximum wall thickness.

c) Design guidelines

Limited to simple shapes. Undercuts not recommended. Thermoplastics require heating and cooling cycles decreasing production rate. Frequently used for particle or short fiber-filled composites

d) Data Sources / Sources for further Information

CES (Cambridge Engineering Selector) Ver. 4.5, Software

Geoffrey Boothroyd, Peter Dewhurst, Winston Knight (2002). Product Design for Manufacture and Assembly. New York, Marcel Dekker.

Dominick Rosato, Donald Rosato, Matthew Rosato, (2004), Plastic Product Material & Process Selection Handbook, Oxford, Elsevier

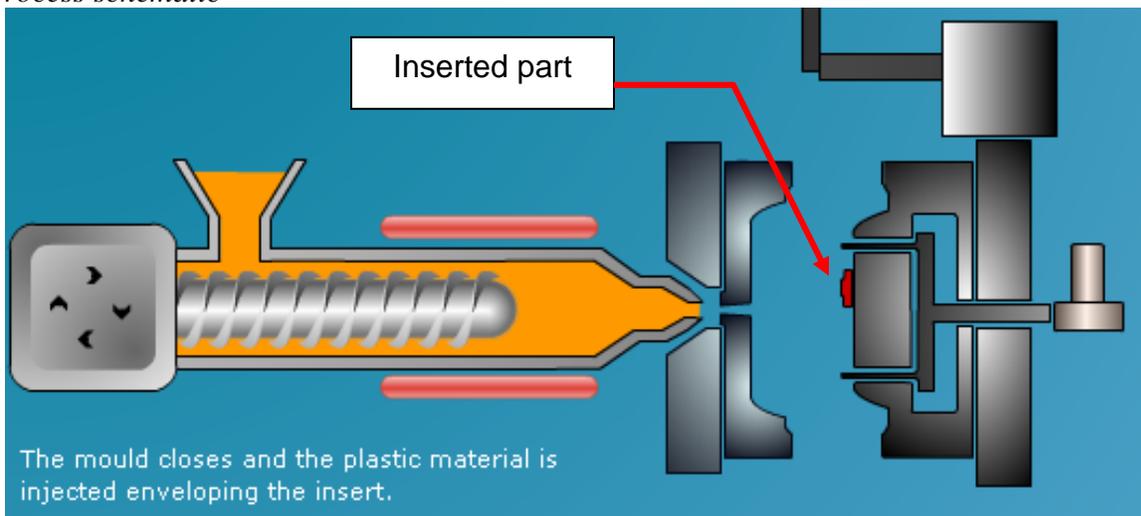
3.2.4 Insert molding

a) Process description and potential materials

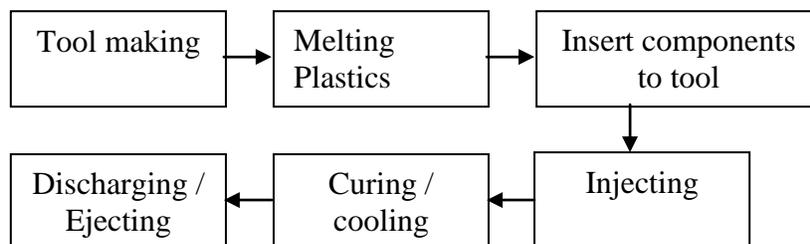
Process description

Insert molding is an exotic form of injection molding where metal (or other material) inserts are molded into the part. Basically, the inserts are manually inserted into the mold before the mold is closed. More automatic processes (which incur higher capital costs) are sometimes used for higher volume parts.

Process schematic



Process flow



Material

Like injection molding in general, insert molding can be accomplished with a wide variety of materials, including polyethylene, polystyrene, polypropylene, polyvinyl chloride, thermoplastic elastomers, and many engineering plastics.

b) Costing information

To cost out an insert mold, use the injection molding module just as it is for your plastic part. Then, add \$.03 per insert to the variable cost.

Example:

Suppose you are adding two inserts per part in a four cavity mold. You are adding 8 inserts per cycle, adding another \$.24 to the variable cost. You must also charge yourself for the inserts, which must be sourced or manufactured.

c) Design guidelines

In general, the basic design rules for insert molding are the same as those that apply to injection-molded parts. The primary factors that restrict the use of insert molding are not process related, but are determined by the strength and other properties required for the molded product.

d) Data Sources / Sources for further Information

CES (Cambridge Engineering Selector) Ver. 4.5, Software

Geoffrey Boothroyd, Peter Dewhurst, Winston Knight (2002). Product Design for Manufacture and Assembly. New York, Marcel Dekker.

http://www.bpf.co.uk/bpfindustry/process_plastics_insert_moulding.cfm (Date: 10/09/05)

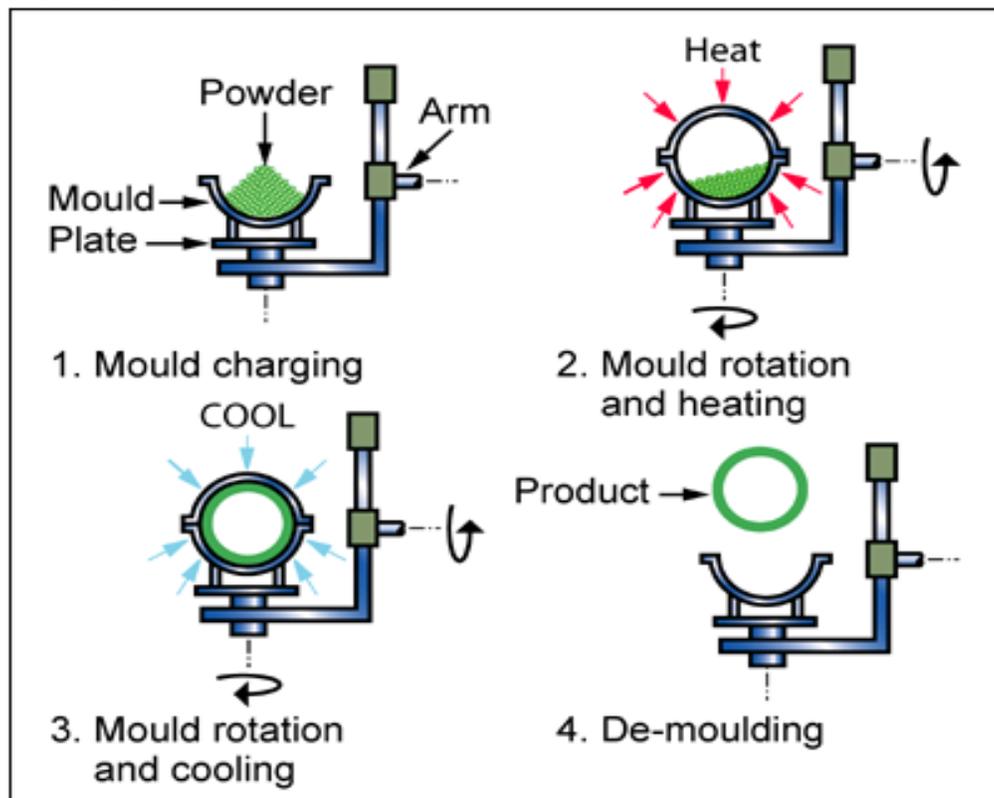
3.2.5 Rotational molding

a) Process description and potential materials

Process description

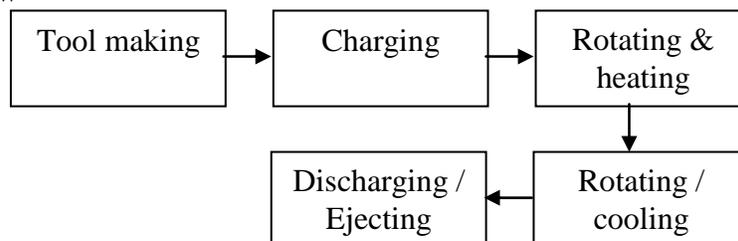
Rotational molding involves placing material in a heated die and slowly rotating. As the plastic melts, it coats the die to the desired thickness. The die is then cooled and parted. To avoid under-utilization of the oven, machines typically have multiple arms, each with at least one mold. While one arm is in the oven, others are undergoing cooling, unloading or loading.

Process schematic



<Source: CES (Cambridge Engineering Selector) Ver. 4.5>

Process flow



Material

Mainly thermoplastics but some thermosets also used. Short fibre composites (mainly glass filled) also produced. PE is the most commonly used thermoplastic. Polyurethane is the most common thermoset

b) Costing information

Rotational molding has the following costs:

- 1) Tooling. The mold must be machined.
- 2) Material costs.
- 3) Molding costs, which include placing the plastic in the mold, heating, cooling, and removing the part

Costing guidelines:

- 1) Machine the molds using injection molding guideline. Each arm must have a mold. They may have multiple molds, and each mold may have multiple cavities as in injection molding part families. Charge yourself for machining all molds in your design.
- 2) Material costs should be documented as described elsewhere.
- 3) Molding operations that take machine and labor time include loading, heating, cooling and removing the part. In a single arm machine, these operations are sequential. In multiple arm machines, assume that the arms rotate at a cycle time equal to the maximum of the heating and cooling cycles (cooling time divided by the number of cooling stations). In the five arm machine for example, each part heats at station 1, cools at 2 and 3, unloads at 4 and reloads at 5.

Assume a loading and unloading time of 20 seconds per part (10 seconds each for loading and unloading).

Heating/coating time is assumed proportional to wall thickness and is assumed to be $20 + 24h$ seconds, where h is the maximal wall thickness in inches.

Cooling time should be assumed to be equal to $60 \times 1.7 \times h^2 / \pi \alpha$ seconds, where

α = thermal diffusivity in $\text{in}^2/\text{minute}$.

If there are multiple cooling stations, cooling takes place at each of these stations. Hence, with s cooling stations, only $1/s$ of the total cooling time must be accomplished at each station. This is an approximation since some cooling stations may be air cool and some water cool. For our purposes, assume a constant thermal diffusivity over all cooling stations.

The charge for the machine and labor time will depend on the number of arms, n . Specifically, charge yourself $20 + 7n$ dollars per hour.

Example: Suppose you want to mold a part out of polycarbonate with maximal wall thickness .2 inches in a five-arm machine described above (one mold per arm).

Mold cost here is five times the cost for machining the mold in the injection molding guideline.

Injection molding guideline gives polycarbonate $\alpha = .012 \text{ in}^2/\text{min}$. So the cooling time is $60 \times 1.8 / 2 = 54$ seconds per cycle. Heating and coating time is $20 + 24(.2) = 24.8$ seconds. Loading and unloading are 10 seconds each. The overall cycle time is then 54 seconds driven by cooling.

The charge for the machine and labor time will depend on the number of arms, n . Specifically, charge yourself $20 + 7n$ dollars per hour. In the example, that is \$55 per hour.

c) Design guidelines

Simple hollow shapes only. Varying wall thickness is possible but difficult. Abrupt changes are impossible. Open shapes (e.g. bins, etc.) are possible through use of insulation in mould. Part length restricted to less than 4 x diameter of part.

d) Data Sources / Sources for further Information

CES (Cambridge Engineering Selector) Ver. 4.5, Software

Geoffrey Boothroyd, Peter Dewhurst, Winston Knight (2002). Product Design for Manufacture and Assembly. New York, Marcel Dekker.

Dominick Rosato, Donald Rosato, Matthew Rosato, (2004), Plastic Product Material & Process Selection Handbook, Oxford, Elsevier

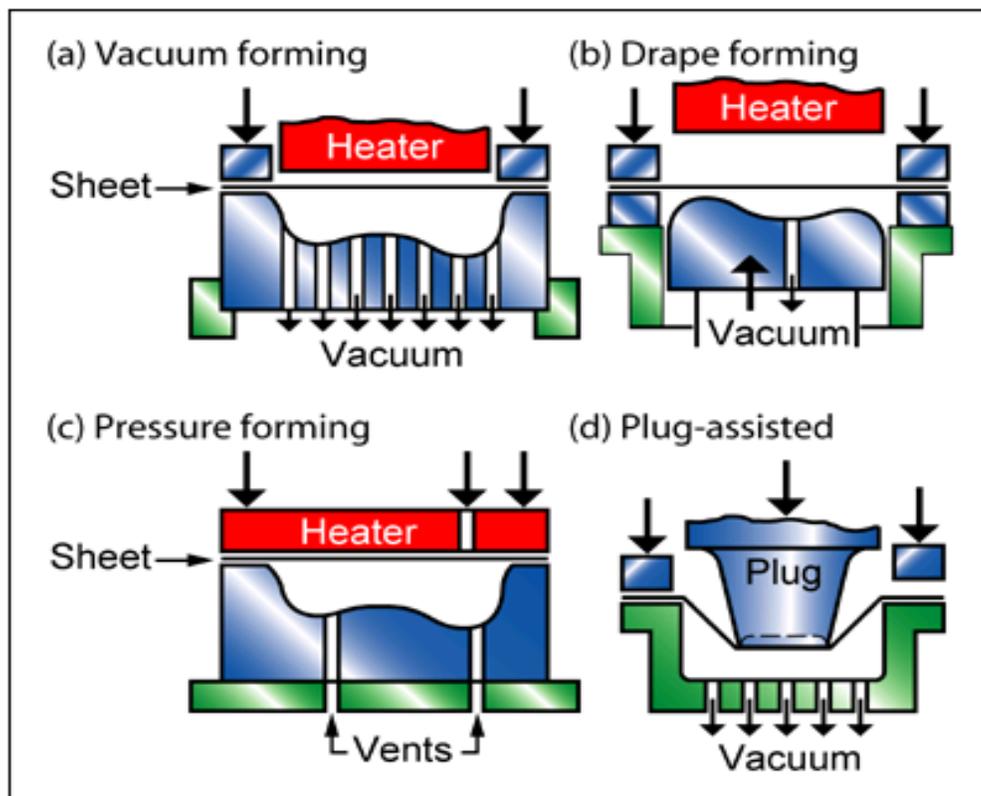
3.2.6 Thermoforming (Vacuum forming)

a) Process description and potential materials

Process description

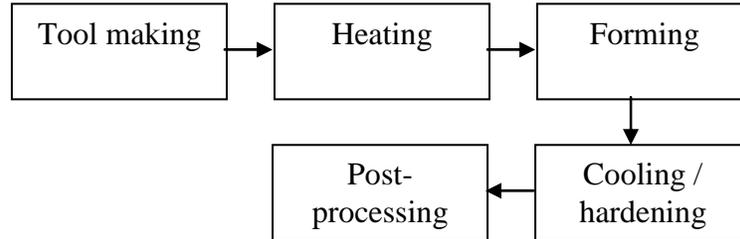
Vacuum forming (or thermoforming) is a manufacturing process in which a sheet of plastic is heated to its deformation temperature, and then is drawn down over a mold by evacuating air between the sheet and the mold, relying on the outside atmospheric pressure to press the plastic down over the mold. The plastic is then allowed to cool in this position, and is ejected. The process is appropriate for parts that can be made by impressing deformations into a flat sheet. For example, simple “shoe box” or “bowl” shapes can be vacuum formed. The cup lids that you place on take-out drinks are vacuum formed. Because the tooling can be rapidly made out of wood or epoxy, vacuum forming is one net shape process that is often used for prototypes.

Process schematic



<Source: CES (Cambridge Engineering Selector) Ver. 4.5>

Process flow

*Material*

The process is used with thermoplastics, foams and short fibre reinforced thermoplastics. ABS, PA, PC, PS, PP, PVC, polysulphones, PBT and PET are particularly suited.

b) Costing information

Commercial vacuum forming involves the following costs:

- 1) Tooling. The mold has to have cooling channels. Prototypes can be done on wood or epoxy molds but these will not last very long in production because they will deform and crack under repeated heating/cooling. Also, wood and epoxy hold heat and the cooling times can be very long. Production molds are commonly made from aluminum, but other metals can be used. The mold must have channels for the air, as well as channels for cooling water.
- 2) Material costs.
- 3) Molding costs, which include clamping the sheet of plastic, heating it up, drawing it down over the mold, allowing it to cool, and then removing it.
- 4) Post processing costs, such as cutting the mold away from the surrounding sheet of plastic.

Costing guidelines:

- 1) Assume that you machine the tool out of aluminum, complete with channels for air. If you are vacuum forming your prototype, then submit the tool with your product launch, and cost out the tool that you actually used in the prototype creation (but assume that you make it out of aluminum). You will need to drill the air channels, but you can ignore the need to drill water cooling channels. You may make as many parts per pull as you wish, but then you must of course machine that many forms. Use the machining guideline to cost out tool construction . If you are not actually vacuum forming your launched product, then draw and cost out the tool that you would have used.
- 2) Material costs include the cost of the entire square or rectangular sheet input into production. Source the material in sheets, and assume 2% yield loss (so charge yourself 1.02 times the cost of each sheet input into production). Be sure to charge yourself for preprocessing to get the big sheet down to the molding size.
- 3) Molding operations that take machine and labor time include clamping, forming, cooling, and blowing the part off the mold. The cost will be driven by the size of the machine needed (which

will be a function of the size of the input sheet of plastic) and the time needed to load, draw, cool, and unload the part.

Assume a loading and unloading time of 20 seconds per pull (10 seconds each for loading and unloading).

Cooling time should be assumed to be equal to $1.7 \times h^2/\pi\alpha$ where

h = maximal wall thickness in inches.

α = thermal diffusivity in $\text{in}^2/\text{minute}$.

For example, suppose you want to vacuum form a part out of polycarbonate with maximal wall thickness .2 inches. Injection molding guideline gives polycarbonate $\alpha = .012 \text{ in}^2/\text{min}$. So the cooling time is 1.8 minutes. Add 20 seconds (.333 minutes) for loading and unloading gives 2.13 minutes.

Actual cycle times for small volume vacuum formed parts are often longer than that (5 - 7 minutes). Thin-walled, high volume parts (such as drink cup lids) can use highly automated ("in-line molding") equipment which reduces the cycle times considerably. This approximate model compromises between the mold times that might be realized with single-station hand-operated molding and completely automated in-line molding.

The charge for the machine and labor time will depend on the size of the input sheet of plastic. Specifically, let S = the surface area (square feet) of the input sheets. Charge yourself

$$20 + (S/36)80 \text{ \$/hour}$$

for the mold and labor time during molding. So, if the rectangular input sheet for the polycarbonate part mentioned above is 1.5 square feet, the time (2.13 minutes) should be costed out at

$$20 + (1.5/36)80 = 23.33 \text{ \$/hour.}$$

Hence, this part will cost $(2.13/60)23.33 = \$.83$ per pull for the molding cost (excluding material).

4) Post processing operations are needed to trim away unwanted material, and finish the resulting edges. These should be charged as hand operations.

c) Design guidelines

Shape capability limited to simple shapes of constant cross-section. Undercuts are possible but increase tooling costs considerably. Holes and openings are not possible without additional processes. Fiber reinforcement may further limit formability.

d) Data Sources / Sources for further Information

CES (Cambridge Engineering Selector) Ver. 4.5, Software

Geoffrey Boothroyd, Peter Dewhurst, Winston Knight (2002). Product Design for Manufacture and Assembly. New York, Marcel Dekker.

Dominick Rosato, Donald Rosato, Matthew Rosato, (2004), Plastic Product Material & Process Selection Handbook, Oxford, Elsevier

3.3 Bulk Deforming Processes

3.3.1 Extrusion

a) Process description and potential materials

Process description

The description below is for aluminum extrusion. Plastic extrusion is very similar and is discussed at the end of this section.

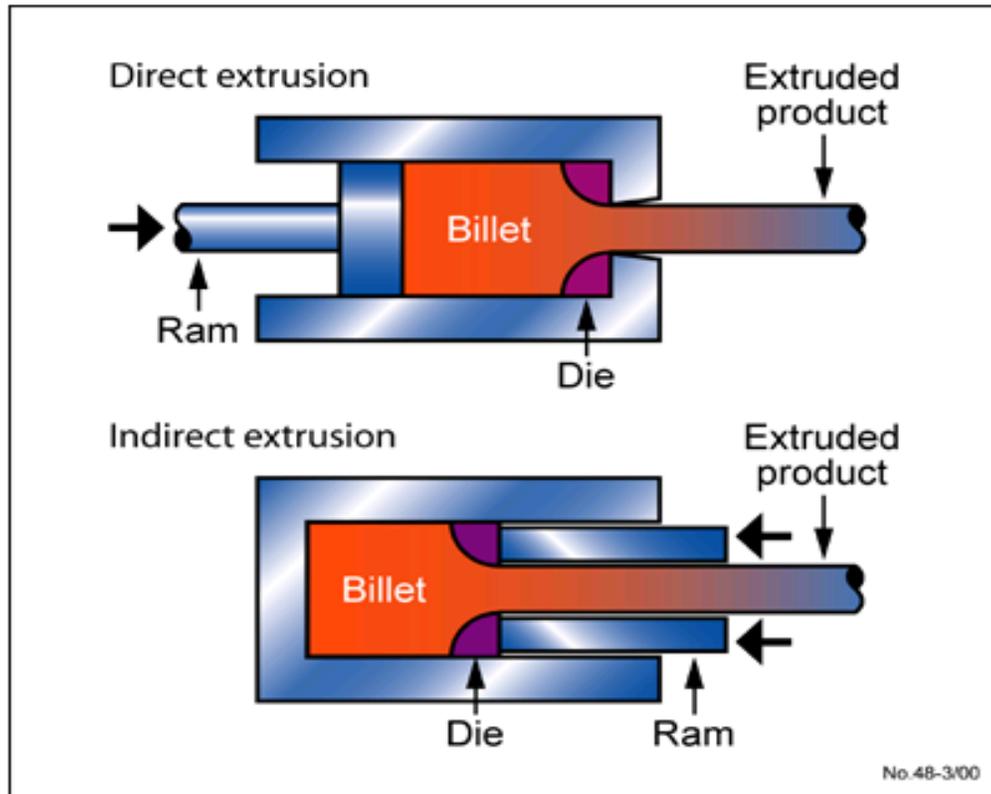
Aluminum extrusion is a process in which a metal billet is heated to between 700 and 900 degrees F. and by means of a hydraulic ram is forced through a die hole. The emerging metal has a cross-section determined by the shape of the die hole. Extruded metal can bend or deform due to different flow rates in different parts of the die (because of different cross-sectional thicknesses) and/or due to differential cooling. Because of this, some post-processing operations may be required to straighten the metal extrusion. The extrusion is then cut to length. The dies for aluminum extrusion are relatively inexpensive.

Before any material can be extruded, a tooling stack (die, die backer, etc.) must be assembled and preheated to operating temperatures. This takes several hours. Also, the first several hundred pounds are used to get the process in control, so this is wasted time. Together, these impose a large set up cost on the manufacturer. Typically, an extruder will not run less than 1000 pounds of material through a die.

An aluminum billet, of a size determined by the length and size of the extrusion, is heated and placed in back of the die. A hydraulic ram then forces it through the die onto a runout table. From there the extrusion is moved to a cooling table where it is stretched to remove twists, etc.

Extrusion dies are relatively inexpensive. A standard flat-shape die can cost about \$500 and use a common backing plate. A hollow die will have a special backer and can cost up to \$1500. More complex dies are more expensive. The extrusion process cannot hold tight tolerances. The extrusion industry depends in large measure on the construction industry, where extruded parts are used for trim (decorative applications where tight tolerances are not essential). Tight tolerances can be achieved by secondary operations on extruded parts, and the combined cost is often very competitive.

Process schematic



<Source: CES (Cambridge Engineering Selector) Ver. 4.5>

Process flow



Material

Wide variety of metals are extruded. The most common are: aluminium and aluminium alloys, copper and copper alloys, magnesium, low-carbon and medium-carbon steels, low-alloy steels and stainless steels

b) Costing information

Fixed cost:

Commodity extruded parts may be sourced wholesale. Custom extrusions require that a die be manufactured. The die cost can be estimated from:

$$\text{Die cost (\$)} = 500 + 500H + 3A$$

where

$H = 1$ if the extrusion includes a hollow shape, and $= 0$ otherwise.

$A =$ area of rectangle circumscribing the part (in²).

Variable cost per part:

The part costs can then be estimated from the materials cost adjusted for post-processing requirements, plus cutoff costs. These can be computed as follows:

Per unit cost (\$/unit) = $M(1 + .1T/t) +$ cutoff cost

where

M (\$/unit) = material cost from the volume of each part and the material selected.

$T =$ thickest wall

$t =$ thinnest wall in the cross section.

Cutoff cost = sawing each part off from the extrusion. Cost this out as in the costing guidelines for hand operations, using a part-off operation so there is one cut per part.

Plastic extrusion

Assume tooling costs as above for plastic extrusions. Close tolerances cannot be held with plastic extrusions. Reasonable surface finishes are available, but there might be some longitudinal "witness lines" from the tool. Post operative smoothing of these is more difficult in plastic. So, plastic extrusions should only be used if tolerances are not that important, and if some small number of witness lines are acceptable.

c) Design guidelines

There will be more postprocessing if the design has

- a) Non-identical thicknesses, since thick sections flow faster than thin ones, the part tends to distort upon leaving the die, and requires more post-extruding time per part.
- b) Hollow shapes add about 10% per part to the cost.
- c) "Semi-hollow" shapes with narrow die sections make for weak die sections and potentially decreased die life.
- d) Longitudinal symmetry in the part is desirable as the part does not deform as much.

d) Data Sources / Sources for further Information

CES (Cambridge Engineering Selector) Ver. 4.5, Software

Geoffrey Boothroyd, Peter Dewhurst, Winston Knight (2002). Product Design for Manufacture and Assembly. New York, Marcel Dekker.

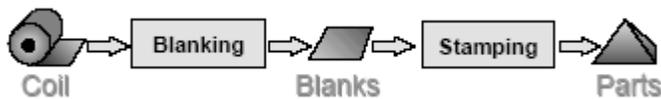
3.3.2 Stamping

a) **Process description and potential materials**

Process description

Most stamping processes comprise two steps. In the first step a shearing operation separates individual blanks of appropriate size from either larger blanks or coils. The second step is the actual forming operation in which the part is drawn in one or several operations (“hits”). The costs - and the design parameters impacting these costs - are discussed below for both steps.

Process flow chart



Material

Stamping is a process that can be applied to most ductile metals.

b) **Costing information**

Blanking

Unless you plan to use a progressive die you will have to create the blanks for the stamping process. The costs for this step include: material cost, machine cost, and tooling costs.

The material costs for the blanking step are the costs per blank. The blank is usually larger than the final part and the portion that is cut off during or after stamping is called *engineered scrap of manufactured scrap*. Clever part layout on the coil can reduce this scrap. The exact blank size is difficult to determine, but at a minimum it should include the part surface plus some material to control the flow of material during drawing (as a rule of thumb minimum 50 mm on all sides) plus extra material for very irregular shapes. The material that is not used for the part will receive scrap credit. For examples of material prices see table 1 below.

The machine costs for the process step blanking are determined by the size of the machine, its speed, and its hourly costs. The required machine size is typically dependent on the blank size and the required shearing force. The bed size of the machine has to be able to accommodate the blank size. Table 2 lists some example machines. The required shearing force depends on the material type, the material thickness, and the length of the cut. As a rule of thumb, you can use the following formula: $f = 0.5 * U * h * l_s$ where f is the required force in kN, U is the ultimate tensile strength, h is material thickness in m, and l_s is the length to be sheared in m. Once the minimum machine size has been identified, hourly costs and run rates determine the machine cost per part for the blanking process.

The tooling costs of the blanking process are determined by the size of the part, material type and thickness, and the shape of the cut. If the cut is a straight line, a non-dedicated shear can be used. If, however, the blank has as its own unique shape then a dedicated blanking tool must be purchased and amortized. For a simple cut-off, just add 10% to the hourly machine rate to

reflect the tool costs. To calculate the tool cost for blanking dies for uniquely shaped cuts use the following formula as a lower bound:

$$C_{ds} = 120 + 0.36 * A_u + \left[32 + \left(\frac{P^2}{L * W} \right) * 0.05 \right]$$

where C_{ds} is the die set cost, A_u is the usable area in cm^2 between the guide pillars of the die set, P is the perimeter length to be sheared in cm, and L and W are length and width of the smallest rectangle that surrounds the punch in cm.

Stamping

The costs for the process step stamping include the costs for machine use and the costs for the stamping dies.

Machine costs for stamping depend on required machine size, machine speed, and the hourly machine rates. Machine size depends on the bed size requirements, and the number of hits required to form the part under consideration. The number of hits is a function of the material's formability, critical measures of the part geometry, and additional part features such as flanges and bends. For steel sheet the following approximation can be used: If the final part resembles more box shape, the critical measure is the ratio of maximum draw depth to minimum draw radius. If this measure is larger than 6 more than 1 hit will be needed, if it is larger than 12 more than 2 hits will be needed to form the part without tearing the material. If the final part resembles more a cylinder, there are two critical measures: (a) the ratio of maximum draw depth to draw area diameter (H/D ratio), and (b) the ratio of material thickness to draw area diameter (t/D ratio). Tables 3 and 4 provide guidance in determining the minimum number of hits for steel sheet. If the part requires additional flanging operation, these are accomplished with additional hits. With the exception of a transfer press that can provide up to 6 hits in one machine, x number of hits mean that the part has to be processed x times. Once required size and number of machines have been identified, run rates (strokes per minute) and hourly machine rates determine the machine cost per part for the stamping process.

The tooling costs for the stamping process depend on the part size and the number of hits. To estimate the costs of the complete tool set you can use the following formulas an approximation:

$$C_{ds} = 1567 * N_{Hits}^{1.366} * \left(\frac{A_{proj}}{A_{final}} \right)^{0.323} * (L * W)^{0.342}$$

where C_{ds} is the tool set costs, N_{Hits} is the number of

hits required, A_{proj} is the projected stamping area in m^2 , A_{final} is the final surface area of the part in m^2 , and L and W are length and width of the final part in mm. Stamping dies are almost always part specific, in other words they are dedicated and have to be amortized across the planned production volume. Stamping tools are expensive, but tend to have a long life time as well (typically several 100,000 units).

Simple approximate models for use in IPD:

Die cost: Using the above and assuming the projected area approximately equals the final area, and changing from mm to inches, yields

$$C_{ds} = 14,320 N^{1.32} A^{.342} (\$)$$

N = number of hits

A = area of part (in²)

Use this model for both blanking dies and stamping dies. So, at minimum we would expect to have two hits, blanking and stamping.

The variable cost = material cost + engineered scrap cost + machine time cost. Assume 10% engineered scrap. So, the total material cost including scrap is just the material cost for the volume input into the dies, multiplied by 1.1. Charge yourself \$.01 per strike for the machine time cost, so the machine time cost is .01N

c) Design Guidelines

Reduce engineered scrap, avoid sharp radii, avoid large draw dept with small diameter (minimize draw depth), observe forming limits.

d) Data Sources / Sources for further Information

CES (Cambridge Engineering Selector) Ver. 4.5, Software

Geoffrey Boothroyd, Peter Dewhurst, Winston Knight (2002). Product Design for Manufacture and Assembly. New York, Marcel Dekker.

Table 1: Sheet Metal Properties and Typical Costs

Alloy	Cost (\$/kg)	Scrap value (\$/kg)	Specific gravity	UTS (MN/m ²)	Elastic Modulus (GN/m ²)	Max. tensile strain
Steel, low-carbon, commercial quality	0.80	0.09	7.90	330	207	0.22
Steel, low-carbon, drawing quality	0.90	0.09	7.90	310	207	0.24
Stainless Steel T304	6.60	0.40	7.90	515	200	0.40
Aluminum, 1100, soft	3.00	0.80	2.70	90	69	0.32
Aluminum, 1100, half hard	3.00	0.80	2.70	110	69	0.27
Aluminum, 3003 hard	3.00	0.80	2.70	221	69	0.02
Copper, soft	9.90	1.90	8.90	234	129	0.45
Copper, 1/4 hard	9.90	1.90	8.90	276	129	0.20
Titanium, Grade 2	19.80	2.46	4.50	345	127	0.20
Titanium, Grade 4	19.80	2.46	4.50	552	127	0.15

Source: Boothroyd, Dewhurst, and Knight (2002)

Table 2: Mechanical Presses

Bed Size		Press force (kN)	Operating cost (\$/hr)	Maximum press stroke (cm)	Strokes (per min.)
Width (cm)	Depth (cm)				
50	30	200	55	15	100
80	50	500	76	25	90
150	85	1750	105	36	35
180	120	3000	120	40	30
210	140	4500	130	46	15

Source: Boothroyd, Dewhurst, and Knight (2002)

Table 3

Number of Hits for Steel 1010 for draw die radii of 4t to 8t							
	t/D ratio						
col_num	1	2	3	4	5	6	
H/D RATIO	2.00%	1.50%	1.00%	0.60%	0.30%	0.15%	
0.46	1	1	1	1	1	1	1
0.47	1	1	1	1	1	1	2
0.53	1	1	1	1	2	2	2
0.63	1	1	1	2	2	2	2
0.71	1	1	2	2	2	2	2
0.85	1	2	2	2	2	2	2
0.91	1	2	2	2	2	2	3
0.95	2	2	2	2	2	2	3
0.97	2	2	2	2	3	3	3
1.14	2	2	2	3	3	3	3
1.31	2	2	2	3	3	3	4
1.37	2	2	3	3	3	3	4
1.61	2	3	3	3	4	4	4
1.89	3	3	3	3	4	4	4
1.91	3	3	3	4	4	4	4
2.01	3	3	3	4	4	4	5
2.31	3	3	4	4	4	4	5
2.41	3	3	4	4	5	5	5
2.71	3	3	4	4	5	5	ERR
2.81	3	4	4	4	5	5	ERR
2.91	3	4	4	5	5	5	ERR
3.31	3	4	4	5	ERR	ERR	ERR
3.51	4	4	4	5	ERR	ERR	ERR
3.61	4	4	5	5	ERR	ERR	ERR
4.11	4	4	5	ERR	ERR	ERR	ERR
4.31	4	5	5	ERR	ERR	ERR	ERR
5.21	4	5	ERR	ERR	ERR	ERR	ERR
5.61	5	5	ERR	ERR	ERR	ERR	ERR
6.61	5	ERR	ERR	ERR	ERR	ERR	ERR
8.91	ERR	ERR	ERR	ERR	ERR	ERR	ERR
ERR	ERR	ERR	ERR	ERR	ERR	ERR	ERR

Table 4

Number of Hits for Steel 1010 for draw die radii of 8t to 15t							
	t/D ratio						
col_num	1	2	3	4	5	6	
H/D RATIO	2.00%	1.50%	1.00%	0.60%	0.30%	0.15%	
0.38	1	1	1	1	1	1	1
0.39	1	1	1	1	1	1	2
0.46	1	1	1	1	2	2	2
0.51	1	1	1	2	2	2	2
0.58	1	1	2	2	2	2	2
0.65	1	2	2	2	2	2	2
0.71	1	2	2	2	2	2	3
0.78	2	2	2	2	2	2	3
0.83	2	2	2	2	3	3	3
0.94	2	2	2	3	3	3	3
1.11	2	2	3	3	3	3	4
1.31	2	2	3	3	3	3	4
1.33	2	3	3	3	4	4	4
1.51	2	3	3	4	4	4	5
1.55	3	3	3	4	4	4	5
1.81	3	3	4	4	4	4	5
2.01	3	3	4	4	5	ERR	ERR
2.21	3	4	4	4	5	ERR	ERR
2.41	3	3	4	5	5	ERR	ERR
2.71	4	4	4	5	ERR	ERR	ERR
2.91	4	4	5	5	ERR	ERR	ERR
3.31	4	4	5	ERR	ERR	ERR	ERR
3.51	4	5	5	ERR	ERR	ERR	ERR
4.11	4	5	ERR	ERR	ERR	ERR	ERR
4.31	5	5	ERR	ERR	ERR	ERR	ERR
5.11	5	ERR	ERR	ERR	ERR	ERR	ERR
6.61	ERR	ERR	ERR	ERR	ERR	ERR	ERR
ERR	ERR	ERR	ERR	ERR	ERR	ERR	ERR

3.3.3 Standard sheet metal forming

a) **Process description**

Sheet metal can be cut on a shear (essentially a large metal scissors that is most often foot or power operated) and/or bent on a “brake” (a form of standard V-shaped stamping die in a hand or power operated machine that puts a corner bend into sheet metal). The latter is a form of stamping in which the die is a standard shape and therefore does not require special tooling (the former clearly requires no special tooling). Therefore the cost for these operations are largely variable labor costs and the tool (machine) time.

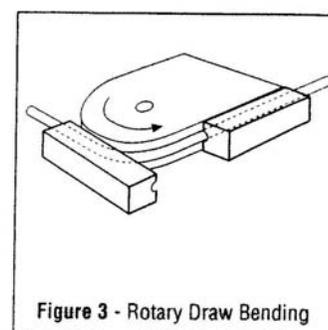
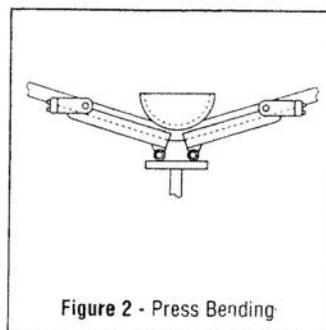
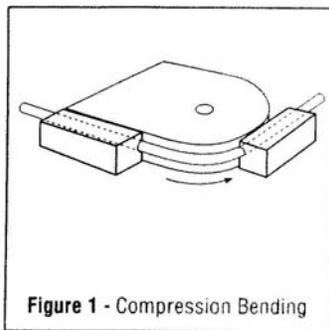
b) **Costing information**

To know whether or not you can assume fabrication on these less expensive machines, ask yourself if you can do the job on a standard hand-operated shear and brake. If the answer is yes, then do so. Time yourself for each bend, working in a careful and deliberate manner. Charge your time at \$15/hour. You do not have to include any tooling cost in your calculations.

3.3.4 Rod, pipe, or tube bending

a) **Process description**

Straight rods, pipes or tubes can be mechanically deformed into bent rods, pipes or tubes. This is done by applying pressure on either the inner or outer (relative to the center of the radius of bend) part of the tube with the other held fixed. When a stationary inner radius block is used and pressure is applied on the outside to force the tube to conform to the radius, it is called a compression method of bending. When pressure is applied to the inner radius by a shaped die (a ram) that forces the tube onto another die (or two “wing die” that pivot around the tube) deforming the tube into the ram shape, it is called ram or pressure bending. When the radius block “rolls” against the tube held by a following block, with one end fixed (like rolling up a garden hose) it is called rotary bending or roll forming.



Three tube bending processes (Ref: Tools for Bending handbook, www.toolsforbending.com)

Variations on these themes involve the rod or tube passing through a series of spool-shaped rollers, each time adding a little more bend to get the desired shape. Sometimes heat is applied to help the material flow more readily into high quality bends.

In all bending operations, the inner wall (toward the center of the radius of curvature) of the tube compresses and the outer wall thins as the tube deforms. For small diameter tubes with relatively thick walls and large bend radii this is not a problem. A rule of thumb is that you can do this relatively easily as long as the “D” factor

$$\text{CLR}/(\text{tube O.D.}) \text{ greater than or equal to } 4$$

where CLR = “center line radius” or radius of the bend at the center of the tube, and O.D. = outside diameter of the tube being bent. Sometimes shops will refer to an “n x D bend” meaning the CLR is n times the O.D. For example, forming is easier for 4xD bends and above.

For larger pipe with thin walls or tight bend radii the tube can wrinkle or fold on the inner radius, and the outer skin stretches across the bend which can deform the tube cross section significantly. Related and in addition, the material on the outer radius will thin and that on the

inner radius will thicken, sometimes until it yields. Several methods are used to help counteract this effect.

- a) The shop can use an inner support (an articulating steel mandrel, or sometimes packed sand) inside the tube.
- b) The tube can be put into compression before bending, so the elongation on the outer radius is from a different starting position.
- b) The shop can heat the inside of the bend which changes the compression yield stress of the material.

For standard radii any tube bending shop will have the appropriate tooling on site. For custom shapes the die will have to be specially built, increasing the fixed tooling cost. The difficulty of the bend and the need for special support tooling will depend on the “D” factor, the “wall factor” (ratio of OD to wall thickness), the desired shape (standard bends, or custom?), the material and the desired quality of the bend (wrinkles, deformations).

b) Costing information

If you can do the job on a standard hand-operated wire former or tube bender using standard radii blocks, and your D-factor (CLR/OD) is greater than or equal to 4, then your costs will be less than if you require a special tool set and special handling. If you are bending to standard radii, your D-factor is at least 4, and you need no special internal mandrels (external wiping blocks are allowed), then you have two options:

- i. No fixed tooling cost: Bend your tube by hand in the shop and time yourself for each bend, working in a careful and deliberate manner. Charge your time at \$15/hour. You do not have to include any tooling cost in your calculations.
- ii. Trade off fixed tooling cost for reduced variable cost: Charge yourself a one-time fixed cost of

$$C_{ds} = 1,000 (\$)$$

dollars for the tool and then charge yourself \$.03 per bend variable cost. Note that you need only pay once for the tool, and you can make as many bends as you wish with it.

If your D-factor is less than 4, then you will need special tooling and other aids to make a quality bend. In that case, charge yourself

$$C_{ds} = 2,000 (\$)$$

dollars for the tool and charge yourself \$.05 per bend variable cost. Again, you need only pay once for the tool, and you can make as many bends as you wish with it.

c) Data sources, sources for further information

Tools for Bending handbook available from web site www.toolsforbending.com

3.4 Machining Processes

a) Process description and potential materials

Process description

In machining, material is removed from the work-piece until the desired shape is achieved. Generally, the machining process is the most costly of the basic forming processes, machining, casting, and deformation processing. However, one avoids fixed tooling costs, so this can be economical for small quantities. Machining is rather fast, the equipment is flexible, and the surfaces generated are usually better than those generated by other processing methods. Common machining processes include turning, boring, milling, drilling, tapping, grinding

Woodworking

Wood can be worked with manual or CNC machines. The primary differences between wood and metal/plastic machining is that wood spindle speeds are not as high (so as not to burn the wood with friction heat), and often carbide tools are used (metal or plastic tools are steel with finer edges but need sharpening more often). A wood machinist can feed about 1/3 faster through wood, even though there is a grain to deal with.

b) Costing information

Use the following guidelines to cost out machining process.

- a) We will ignore the load and unload times and also the tool set and engage times. The former can be significant for large (e.g. crane lifted) parts, but for most parts in the IPD class these costs are small relative to the material removal times.
- b) Find the material removal time from the simple computations below, where you take total volume removed and find the time from a generic material removal rate formula.
- d) Cost out all of these times at the machine rate of \$30/hour in IPD. Actual machine rates in industry are \$30 to \$60 per hour, but hand machining will not be the process of choice for commercial production. The assumed \$30/hour is to take into account the fact that in large volumes, fixtures and other efficiency enhancing steps will be taken to speed higher volume production of your part.

In summary,

$$\text{Cost} = M \cdot T_m$$

where

M = machine rate (use \$30/hour)

T_m = actual machine operation time in hours

= total volume removed (V_t) divided by the volume removal rate (V_r)

Find a generic material removal rate from below formula.

Material removal rate: (generic model)

The time necessary to complete an operation is estimated from the volume of material removed, the material being worked, and the tool used. The basic rate of material removal is:

$$\frac{.0015 \times F \times S}{OP} \text{ (in}^3\text{/min)}$$

where

F = number of flutes (cutting edges) in the tool being used. For saw blades assume F = 1.

S = cutting speed and depends on the material being worked (e.g. appropriate values would be S = 100 for low carbon steel, 200 for brass, 300 for aluminum, 500 for plastics, 750 for wood).

OP = 1 unless listed individually in Table 3 below.

This formula is referred to below.

A. Hand sawing, horizontal cut-off saw and band saw: Assume that the blade width is .035", so that the volume (in³) removed is the cross-sectional area being sawed (in²) multiplied by .035. Assume F = 1 and use an operations factor of 3. For example, a saw can remove metal from a low carbon steel rod at a rate of $.0015 \times 1 \times 100 / 3 = .05 \text{ in}^3\text{/min}$. The metal removed from a 1" diameter rod is $\pi \times .5^2 \times .035 = .0275 \text{ in}^3$, so that the time to saw through this rod will be $.0275 / .05 = .55$ minutes or 33 seconds. Charge sawing time at 30 \$/hour.

B. Drill press: Use an operations factor of 1.5. For example, a two-fluted drill can remove low carbon steel at a rate of $.0015 \times 2 \times 100 / 1.5 = .2 \text{ in}^3\text{/min}$, and to drill a 1/2" diameter hole 1" into low carbon steel will take $\pi \times .25^2 / .2 = .98$ minutes. Center punching in preparation for drilling is a hand operation. Charge time at 30 \$/hour.

C. Reaming and countersinking: Countersinking should be charged at \$.05 per hole. For reaming operations, compute the time as if the ream were drilling with a double fluted (F = 2) drill. That is, as if you were actually removing all material in its path. This assumption is justified by the fact that, although the material removed in a reaming operation is small, you must move slowly to maintain a good surface finish.

D. Tapping (hand threading): Assume the volume removed is $.433 \pi DPL$ where D = diameter (in), P = pitch (in/thread) and L = length (in); assume F = 1. Use the generic material removal rate equation.

E. Other hand processes (guidance by eye/hand using hand-held tools, such as a belt sander, and/or painting by hand): Estimate the time you spend, working at a realistic but efficient pace, and charge at 15 \$/hour.

c) Design guidelines

Consider tool access and cutting path length as cost drivers. You also have to hold the part somehow while you are working on it, and this imposes process sequencing constraints.

d) Data Sources / Sources for further Information

CES (Cambridge Engineering Selector) Ver. 4.5, Software

Geoffrey Boothroyd, Peter Dewhurst, Winston Knight (2002). Product Design for Manufacture and Assembly. New York, Marcel Dekker.

Robert C. Creese, M. Adithan, B.S. Pabla. (1992). Estimating and Costing for the Metal Manufacturing Industries. New York, Marcel Dekker.

Table 3. Operations factors for IPD operations

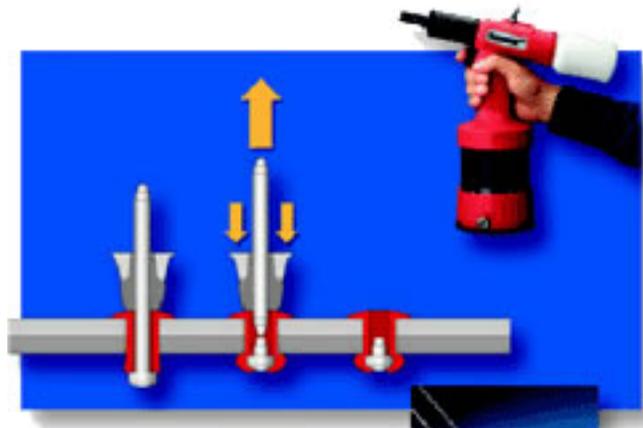
<u>Operation</u>	<u>OP</u>	<u>Additional notes</u>
Drill	1.5	F typically 2, but specify explicitly
Ream	1.5	Compute as if drilling w/F = 2.
Saw	3.0	Assume F = 1.
Center drill	4.0	Assume volume removed is $.226D^3$ (in ³) where D = diameter of center drill in inches.
Hand threads (tap or die)	4.0	Volume removed = $.433\pi DPL$ where D = diameter (in), P = pitch (in/thread) and L = length (in); assume F = 1.

3.4 Joining Processes

3.4.1 Clinching

a) Process description and potential materials

Clinching is a combination of drawing and forming that locks together layers of sheet metal. Multiple layers can be joined, though clinching is most commonly used for only two layers. The method can replace spot welding, riveting, metal screws, brazing, and staking or crimping. In clinching, a punch drives the two layers of metal into a die that produces an impression. Additional force spreads the upper layer of material into the lower layer so it cannot be pulled out.



Source: http://www.hbm.com/uploads/images/solutions/app132_mm_nieten.jpg (10/10/05)

Factors limiting clinching are mainly joint thickness and the distance of the joint from the edge of the material. Both these limits vary with the tooling vendor chosen. Joint thickness is generally limited to a total of 0.25 to 0.30 in., but minimum joint-to-edge distances may range from 0.06 to 0.25 in.

Clinching applications include automotive and appliance assemblies, furnaces and ductwork, housings and enclosures, and metal office furniture.

b) Costing information

- Overall Formula: Charge 3 seconds (\$.01) per fastener.

c) Design guidelines

Two basic clinching methods are used. The older one, often called a clinched or lanced lock, shears the metal, forcing the top layer through slits in the bottom layer. This method is primarily used for metals with less ductility, such as hard aluminum or

stainless steel, or where there is a considerable thickness or ductility difference between the sheets being joined.

The second method, called a button or round clinch, produces no hole but simply deforms both layers so that the bottom layer locks around the top, like a circular dovetail joint. This joint is often preferred because of its neater appearance and leak resistance.

Both processes require use of ductile sheet metals, such as steel, aluminum, or brass in light gauges. Many plastics are difficult to clinch because they tend to resume their original shape after being clinched. Materials that cannot be properly clinched often can be locked between two layers of metal, however.

Note that pem nut installation does not include turning a screw or bolt into the installed nut, which must be costed separately as installing a "threaded fastener." Fasteners that plastically deform and do not come off easily once applied includes rivets and pem nuts.

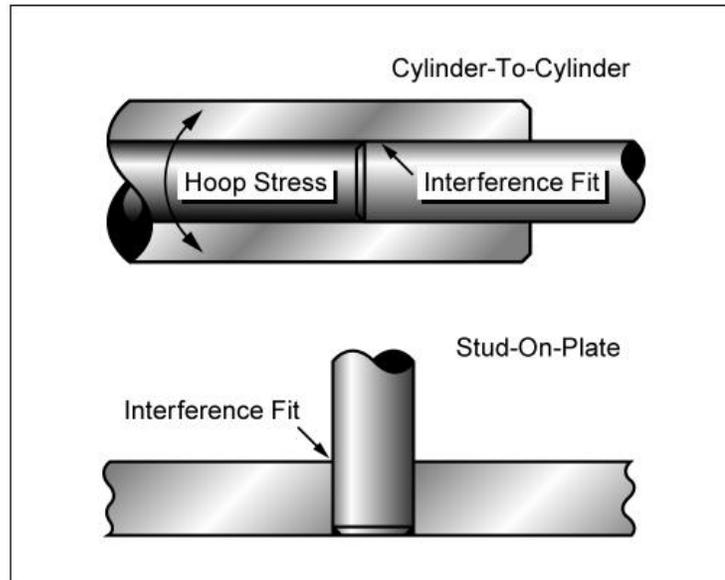
d) Data Sources / Sources for further Information

http://www.machinedesign.com/BDE/FASTENING/bdefj1/bdefj1_9.html (10/10/05)

3.4.2 Press fit

a) **Process description and potential materials**

Press fits offer a very inexpensive, quick and efficient joining method. Press fit must be designed with great care to avoid excessive hoop stress in the assembly. They are widely used to assemble metal parts; they are sometimes used with polymers, but cracking and stress relaxation and loosening over time can be problems.



Source: CES software

Press fits are widely used to join metals. Polymers with a yield strain of 0.01 or above and sufficient strength to tolerate the hoop-stresses can be joined, but press fits are not generally recommended for primary, load-bearing joints with polymers.

b) **Costing information**

- Overall Formula

Charge 15 seconds (\$.06) for each fit if you use a press, otherwise charge the actual time spent in the motion.

c) **Design guidelines**

An application example of press fit can be found in PCB assembly. A press-fit connection is made, as the name implies, through the pressing in of a contact pin into a PCB through hole. The important consideration here is that the cross section of the pin is greater than the diameter of the PCB hole. This difference in pin cross section and hole diameter results in a deformation of either the PCB hole or the cross section of the pin during the insertion process of pin into PCB through hole.

The interference between the press-fitting parts requires precise control. An interference strain of 0.0005 – 0.001 is appropriate for metal-to-metal parts, of 0.007 – 0.008 for polymer-onto-steel and 0.008 – 0.011 for polymer-on-polymer.

Hand assembly requires very little requirement. Automated assembly requires equipment that can be expensive. All parts must be cleaned before assembly. Avoid press fits between different materials when the assembly will be subjected to thermal cycling or when the assembly will be subjected to harsh environments during manufacture, assembly or transport.

d) Data Sources / Sources for further Information

- CES software
- <http://www.ept.de/englisch/produkte/pc104/pc104us.pdf> (10/04/05)

3.4.3 Sewing

a) Process description and potential materials

In sewing, a series of stitches are applied, using one or more continuous threads of fibers, to join two or more thicknesses of material. It provides not only mechanical fastening, but also decoration, often of a very elaborate kind.

Sewing is an exceptionally flexible process, both in the range of materials it can join and in the shapes to which it can be applied. Dissimilar materials can be joined. The threads used for conventional sewing are the natural fibers cotton, silk and flax, the cellulose derivative (rayon or viscose), and drawn polymer fibers made from polyethylene, polyester, polyamide (nylons) or aramids (Nomex, Kevlar). It is also possible to sew with metal threads. The joining thread or fiber must be sufficiently strong and flexible to tolerate the tensions and curvatures involved in making a stitch. All fabrics, paper, cardboard, leather, and polymer films can be sewn. Sewing can also be used to join fabric and film to metal, glass or composite if eye-holes for the threads are molded or cut into these.

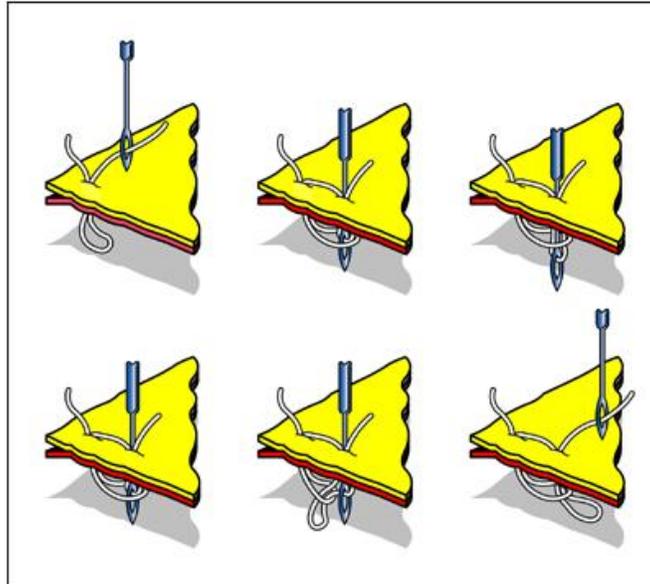
b) Costing information

The actual sewing process would include cutting out the pattern, and then pinning, aligning, and all other necessary manipulations, as well as the actual stitching. Our model is very simple. We ignore cutting out the pattern, and we note that a good line sewer can sew approximately 2.5 yds (90 inches) per minute on average, and their average cost is approximately 36.5 cents / minute, which implies a sewing cost of $.365/90 = .0041$ \$/in. For the sake of simplicity we ignore the various types of stitches and the varying levels of difficulty, for example for sewing thin fabrics (e.g. silk or chiffon) or joint areas (e.g. sleeve to main body).

So to compute your variable sewing costs in dollars simply measure the total length of all of your stitching and multiply by .0041.

c) Design guidelines

There are many types of stitching, broadly described as 'lock stitch' in which loops of one thread pass through the material and are locked on the other side by a second thread; or 'chain stitch' in which a single thread zigzags through the material. Sewing machines automate the process. The figure below shows a chain stitch of a single lap joint.



Source: CES software

There are many possible joint configurations, some involving simple through-stitching of a single lap or zigzag stitching across a simple butt, others requiring folding to give locked-lap and butt configurations.

d) Data Sources / Sources for further Information

CES software

<http://www.bls.gov/oco/cg/cgs007.htm> (09/28/05)

Shaun Jackson Designs personal communication

3.4.4 Shrink fit

a) Process description and potential materials

There are two types of shrink fitting. First uses induction heating to quickly heat the tool holder (target housing) and allow the tool shank (bushing) to slip into the holder before it cools. It is used in high-volume production applications. Second shrink fit is facilitated by chilling the bushing using a suitable media, such as liquid nitrogen, dry ice, or placing the bushing within a freezer. Cooling down the bushing is preferred rather than heating the target housing. Normally, the bushing is of significantly less mass than the target housing, though heating the housing and simultaneously cooling the bushing is not uncommon.

b) Costing information

- Overall Formula
Charge \$.15 for each fitting.

c) Design guidelines

When a bushing or bearing are pressed into a housing, the force driving the bushing bearing should be applied equally or uniform to the end of the bearing to avoid galling, peening or damaging the bushing/bearing. The mating surfaces of both the bushing and housing should be thoroughly cleaned and imperfections as well as burrs removed.

d) Data Sources / Sources for further Information

- <http://www.sme.org/cgi-bin/get-mag.pl?&&04fem006&000007&2004/04fem006&ARTME&SME&> (10/03/05)
- http://www.engineersedge.com/bearing/bushing_press_fit.htm (10/03/05)

3.4.5 Snap fits (including retaining rings)

a) Process description and potential materials

Snap-fit joints are the most widely used way of joining and assembling plastics. They are classified according to their spring element and by separability of the joint: Will it be detachable, difficult to disassemble, or permanent? The most common snap fit is the cantilever. It is based on a flexural beam principle where the retaining force is a function of the material's bending stiffness. The second most widely used is the torsional snap joint. Deflection comes from torsional deformation of the joint's fulcrum and shear stresses carry the load after assembly.

b) Costing information

- Overall Formula

Consider these instantaneous and charge nothing for time.

c) Design guidelines

Materials costs must be accounted for in the materials section of your estimate

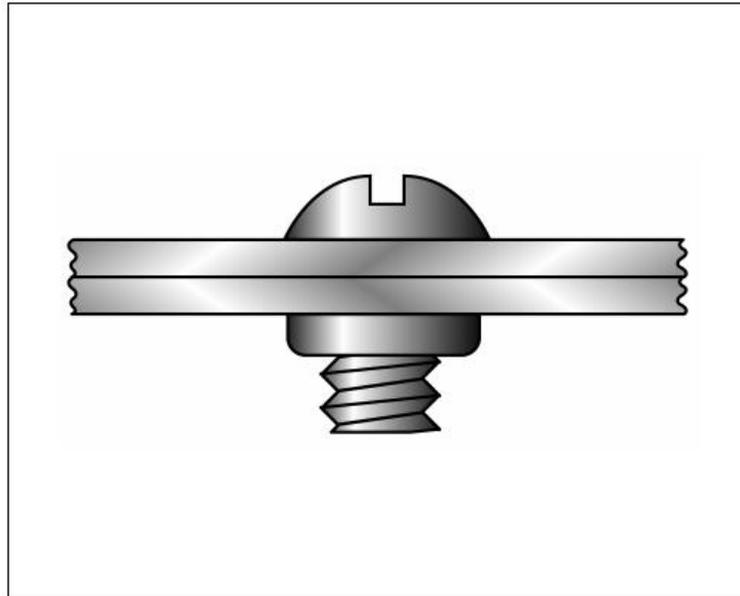
d) Data Sources / Sources for further Information

- <http://www.machinedesign.com/ASP/viewSelectedArticle.asp?strArticleId=57767&strSite=MDSite&catId=0> (10/04/05)

3.4.6 Threaded fasteners

a) **Process description and potential materials**

Two very basic types of machine-threaded fasteners are nuts & bolts and screws. Threaded fasteners are the most versatile of mechanical fasteners, with all the advantages they offer: they do not involve heat, they can join dissimilar materials of very different thickness and they can be disassembled.



Source: CES software

Their great advantages include the ease of assembly, which generally requires no special equipment, as well as the possibility to de- and re-assemble without (much) damage to the joint. They may be used for most materials.

Typical use is for structural assembly in a wide range of engineering applications, particularly where high strength is required. They can also be found in smaller form in for example components where de- and re-assembly may be required (e.g. in domestic electronics).

Threaded fasteners are commonly made of carbon steel, stainless steel, nylon or other rigid polymers. Stainless steel and nickel alloy screws can be used at high temperatures and in corrosive environments. Tightening is critical: too little, and the fastener will loosen; too much, and both the fastener and the components it fastens may be damaged – torque wrenches overcome the problem. Locking washers or adhesives are used to prevent loosening.

b) Costing information

- Overall Formula
Charge 12 seconds (\$.05) per fastener.

c) Design guidelines

Require a significant turning motion to attach or unattach.

Nuts & bolts are generally used with pre-drilled holes. In the case of a nut and bolt, a simple hole will do. Access from both sides of the component during assembly is generally required, although this may not be necessary if captive or welded nuts can be used. Because of their relatively high cost, nuts & bolts are mainly used for thicker sections, where they are a well-established technique.

Self-tapping or thread-forming screws, on the other hand, require no nuts or tapped holes. Mostly used with pre-drilled holes (although self-drilling screws are available (see below)), the screw forms a thread in the materials being joined when inserted, avoiding the need for tapping of the hole or for access to both sides. Flow drilling (causing the material around the hole to be extended beyond the normal material thickness) usually provides enough material for thread engagement, although if required an additional nut or clip may be used.

Self-drilling screws may be used without the need for pre-drilled holes. In thin materials, a screw with a special tip can be used to flow drill the hole in the material, providing additional thread engagement.

To avoid injury to operators, some care may need to be taken with regards to sharp objects, drilling operations and the risk of entrapment of fingers. Furthermore, if pneumatic or hydraulic equipment is used, safety goggles should be worn.

d) Data Sources / Sources for further Information

- CES software
- http://www.twi.co.uk/j32k/protected/band_3/kschjg003.html (10/04/05)

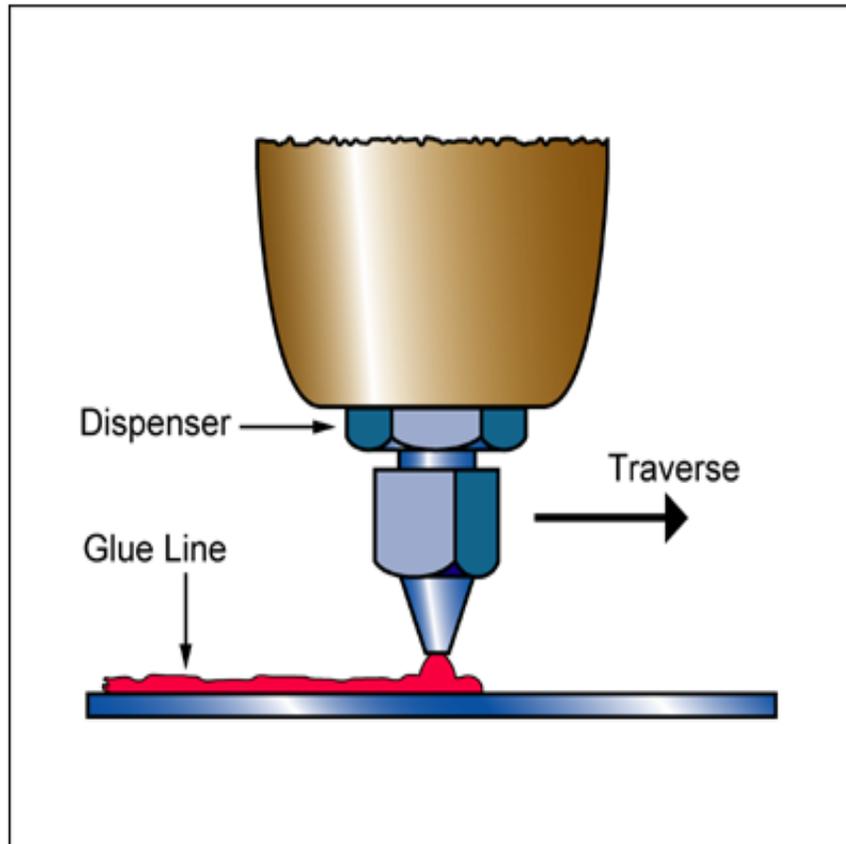
3.4.7 Adhesive bonding

a) **Process description and potential materials**

Process description

Adhesive bonding joins multiple parts using liquid or solid adhesive material. Apply adhesive material on one side of part and join parts then dry to harden.

Process schematic



<Source: CES (Cambridge Engineering Selector) Ver. 4.5>

b) **Costing information**

For nonmetal adhesives (e.g. contact cement, epoxy, solvent cement, or cyanoacrylate (CA) bonding), charge yourself as follows. For spots, charge yourself .2 minutes (\$.05) per spot. Charge yourself $.2 + .05L$ minutes to draw a bead, where L is the length of the bead in inches. Charge yourself $.2 + .4a$ minutes for bonding a surface area of a in^2 . Cost out the time at \$15/hour.

c) Design guidelines

Suggested adhesives

	Metals	Wood	Polymers	Elastomers	Ceramics	Fiber-composites	Textiles
Metals	Acrylic, CA, Epoxy, PU, Phenolic, Silicone			Key CA = Cyanoacrylate Ceram = Ceramic-based Hot-melt = Thermoplastic PES = Polyester PU = Polyurethane PVA = Polyvinylacetate			
Wood	Acrylic, Epoxy, Phenolic, Hot-melt	Epoxy, Phenolic, PVA					
Polymers	Acrylic, CA, Epoxy, Phenolic	Acrylic, PU, Phenolic, PVA	Acrylic, CA, Epoxy, Phenolic				
Elastomers	CA, Epoxy, Silicone	Acrylic, Phenolic, Silicone	AC, Epoxy, Phenolic, Silicone	PU, Silicone			
Ceramics	Acrylic, CA, Epoxy, Ceram	CA, Epoxy, PVA, Ceram	Acrylic, Epoxy, PU, PVA, Ceram	Acrylic, Epoxy, PU, PVA, Silicone	Acrylic, CA, Epoxy, Ceram		
Fiber-composites	Acrylic, CA, Epoxy, Imide	Acrylic, CA, Epoxy, PVA	Acrylic, Epoxy, PVA, Silicone	Epoxy, PU, Silicone	CA, Epoxy, Silicone	Epoxy, Imide, PES, Phenolic	
Textiles	PU, Hot-melt	Acrylic, PVA, Hot-melt	Acrylic, PVA	Acrylic, PU, PVA	Acrylic, PU, PVA, Hot-melt	Acrylic, PU, PVA	PVA, Hot-melt

d) Data Sources / Sources for further Information

CES (Cambridge Engineering Selector) Ver. 4.5, Software

Mike Ashby and Kara Johnson (2002), Materials and design : the art and science of material selection in product design

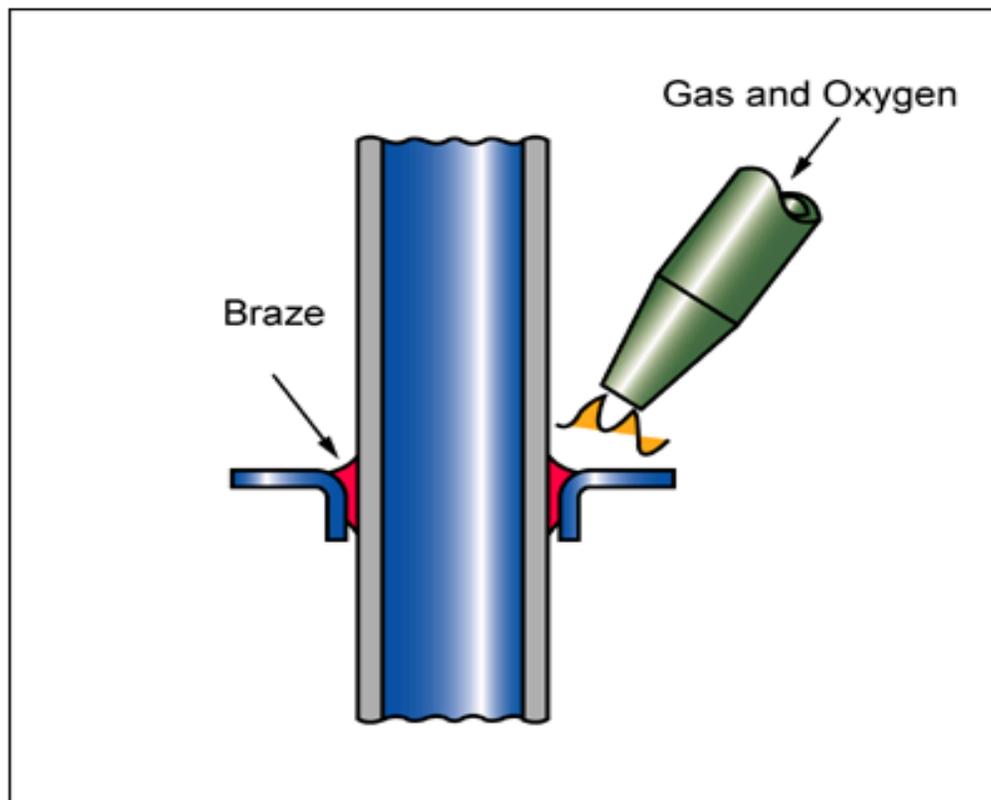
3.4.8 Brazing (Silver brazing)

a) Process description and potential materials

Process description

When the components to be joined cannot tolerate the temperatures required for welding, the alternatives are brazing, soldering, mechanical fasteners or adhesives. Brazing is the hottest of these. In brazing a low melting temperature metal is melted, drawn into the space between the two solid surfaces by capillary motion, and allowed to solidify. Most brazing alloys melt above 450 C but below the melting temperature of the metals being joined. The braze is applied to the heated joint as wire, foil or powder, coated or mixed with flux, where it is melted by a gas-air torch, by induction heating or by insertion of the components into a furnace; the components are subsequently cooled in air.

Process schematic



<Source: CES (Cambridge Engineering Selector) Ver. 4.5>

Material

Almost all metals can be joined by some variant of brazing, provided they have melting temperatures above 650 C.

b) Costing information

Charge 2 minutes (\$.50) per joint plus materials cost of \$.25 per square inch of surface brazed.

c) Design guidelines

The process can join dissimilar metals even when they have different melting temperatures. Brazing is easily adapted to mass production (cheap bicycles are brazed) and the joint is strong, permanent and durable. A large joint area is good - it compensates for the relatively low strength of the brazing metal itself. Joints need a clearance of 0.02-0.2mm to allow a good, strong bond to form. Ceramics can be brazed if the mating surfaces are first metalized with copper or nickel.

d) Data Sources / Sources for further Information

CES (Cambridge Engineering Selector) Ver. 4.5, Software

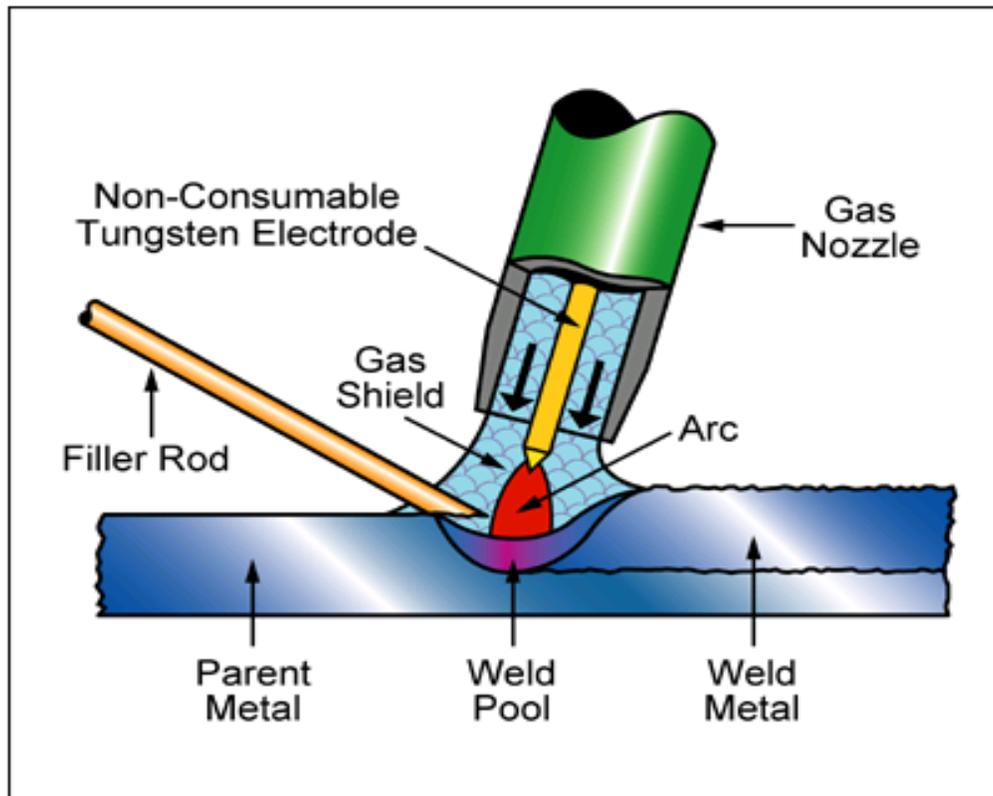
3.4.9 Gas welding (Tungsten inert gas)

a) **Process description and potential materials**

Process description

Tungsten inert-gas (TIG) welding is a heavy-duty welding process (others are MMA and MIG) is the cleanest and most precise, but also the most expensive. In one regard it is very like MIG welding: an arc is struck between a non-consumable tungsten electrode and the work piece, shielded by inert gas (argon, helium, carbon dioxide) to protect the molten metal from contamination. But, in this case, the tungsten electrode is not consumed because of its extremely high melting temperature. Filler material is supplied separately as wire or rod. TIG welding works well with thin sheet and can be used manually, but is easily automated. Both penetration and deposition rates are much less than those of MIG welding, but precise control of the weld is easier.

Process schematic



<Source: CES (Cambridge Engineering Selector) Ver. 4.5>

Material

Almost any metal

b) **Costing information**

Charge \$.06 to start a bead and then assume a bead can be run for a cost of .06 \$/in. Spot welds are assumed to have no "length" and consequently cost \$.06 each. The total number of beads,

along with inches welded per bead will determine the welding cost. This cost is for the welding operation only. Welding can deform material due to thermal stresses. Any post-weld operations like abrading or straightening must be charged as separate operations.

c) Design guidelines

Because the heating is de-coupled from the filler supply, greater control of weld conditions is possible. Thus, TIG welding is used for thin plate and for precision assemblies, made of almost any metal. Clean surfaces and well-prepared joints are important. It's principally used for thin sections and precisely made joints.

d) Data Sources / Sources for further Information

CES (Cambridge Engineering Selector) Ver. 4.5, Software

3.4.10 Vinyl bonding

a) Process description and potential materials

Process description

Vinyl bonding is like vinyl “welding” in that pieces are melted together by a heated press. For example, to make photo sleeves the manufacturer may place down two 3’ by 3’ sheets of vinyl. Then, a press-like structure comes down with tooling of the appropriate configuration and welds the vinyl as in a heat strip operation. Then, the individual pages are cut out of the 3’ by 3’ sheet.

b) Costing information

In practice a tool is made to the correct configuration. In this course, however, reasonable costs can be gained by assuming that the bonding is done by hand using a roller heat tool. Charge the same as nonmetal adhesives at $.2 + .05L$ minutes, where L is the bead length. Charge out cutting the vinyl as a hand operation (hand-done time charged at \$15/hour).

c) Design guidelines

d) Data Sources / Sources for further Information

Dominick Rosato, Donald Rosato, Matthew Rosato, (2004), Plastic Product Material & Process Selection Handbook, Oxford, Elsevier

4. Hand assembly

For hand operations not covered in these guidelines, perform the task yourself at a careful and deliberate speed, and charge your time at \$15/hour.

5. Paperboard packaging

For paperboard packaging with simple printing we assume no fixed costs and the manufacturing variable cost equals the material cost, so the total variable cost = twice the material cost.