Engineering Design I: Methods and Skills
Topic Readings

Steven H. Collins

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Chapter 10

Manufacturing and Cost

So far, we have mostly considered the manufacture of single prototypes using conventional machining and rapid prototyping techniques. These techniques are typically not economical for mass production of products. Here we will discuss a wider range of manufacturing methods and their selection. This type of manufacturing often occurs in phases. **Primary manufacturing processes**, such as molding, create general shapes. **Secondary processes**, such as machining, modify basic shapes from the primary processes to add features. **Finishing processes**, such as painting, are used to change the surface of a item to achieve a certain property. Finally, finished parts must be **assembled** efficiently, which also influences design choices.

We will find that the **quantity** of parts to be produced is a dominant factor in selecting a cost-effective manufacturing technique. Geometric properties of the design, such as qualitative shape, overall size, feature size, and precision also interact with the cost and applicability of different manufacturing processes.

Manufacturing processes

Primary manufacturing processes include **metal casting** in which molten metal solidifies in mold cavity, **polymer molding** in which liquefied polymer is injected into mold, **deformation** by forging, rolling, extruding or bending, primarily of metals, and **additive manufacturing** in which powder particles such as metal, ceramic or polymer are deposited in thin layers and selectively melted together.

Secondary processes include: **machining**, including milling, turning, drilling, tapping or grinding; **joining** processes such as welding, soldering, riveting, and boding; and **heat treatment** processes like hardening and carburizing.

Manufacturing Systems

Manufacturers can be usefully differentiated by the quantities of components they are positioned to produce, the time required to change the parts they are manufacturing, and the level of automation. **Job shops** typically produce small numbers of parts and can retool quickly. For example, a shop might produce 100 custom machined joints for a robotics firm. **Batch** manufacturing systems typically produce intermittent runs of larger numbers of parts, and take longer to retool. For example, a company might produce 10.000 specialized screws for an aeronautics company once or twice a year. **Assembly line** systems create large numbers of sets of identical parts, and tend to be more specialized and inflexible. For example, an automobile company might produce 100,000 cars of the same model in one year. **Continuous flow** systems produce large quantities of highly specialized parts or materials and are highly inflexible. For example, a paper mill might produce 500,000,000 identical rolls of toilet paper in a month. As economical volume of output increases across these systems, so does automation, with concomitant decreases in flexibility.

Selecting Candidate Manufacturing Methods

To select a manufacturing process we need to

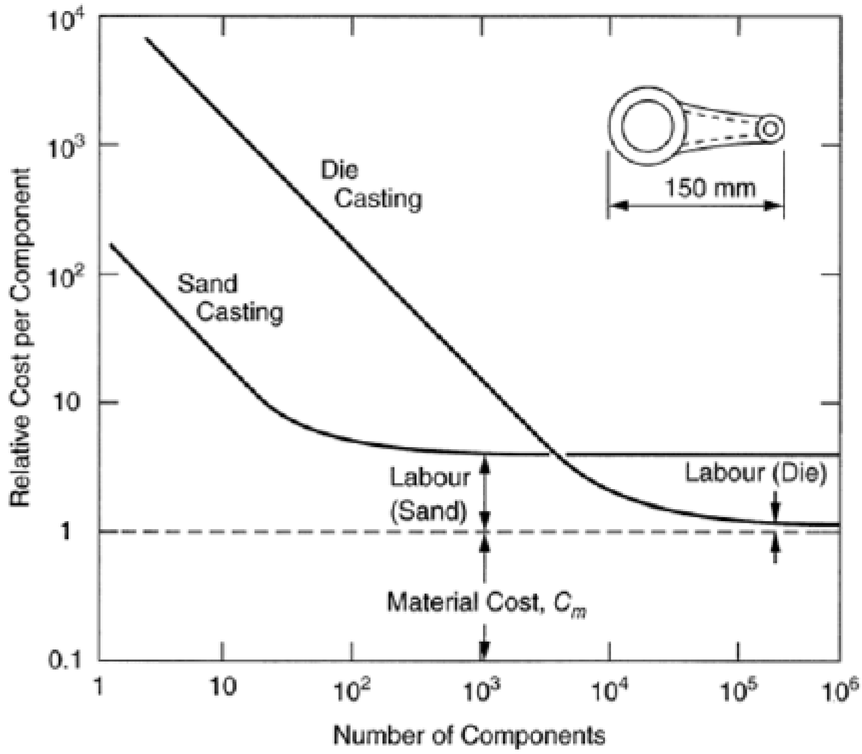
- Identify constraints and objectives,
- find candidate methods that meet constraints, and then
- compare expected outcomes, e.g. cost.

In making this selection, we need to consider factors like **quantity**, **complexity**, **material**, **quality requirements**, **cost and timing constraints**.

Quantity

Manufacturing costs can be usefully divided into two categories. **Fixed costs** must be incurred in order to make a single part, typically before production can begin. For example, a mold might need to be fabricated or a specialized machine built. **Variable costs** are linked to the production of each subsequent part, and are therefore typically proportional the overall quantity. For example, raw materials might be purchased to fabricate each component. The **total cost** of producing a quantity of parts is simply the sum of the fixed and variable costs. The **unit cost** is simply the total cost divided by the quantity.

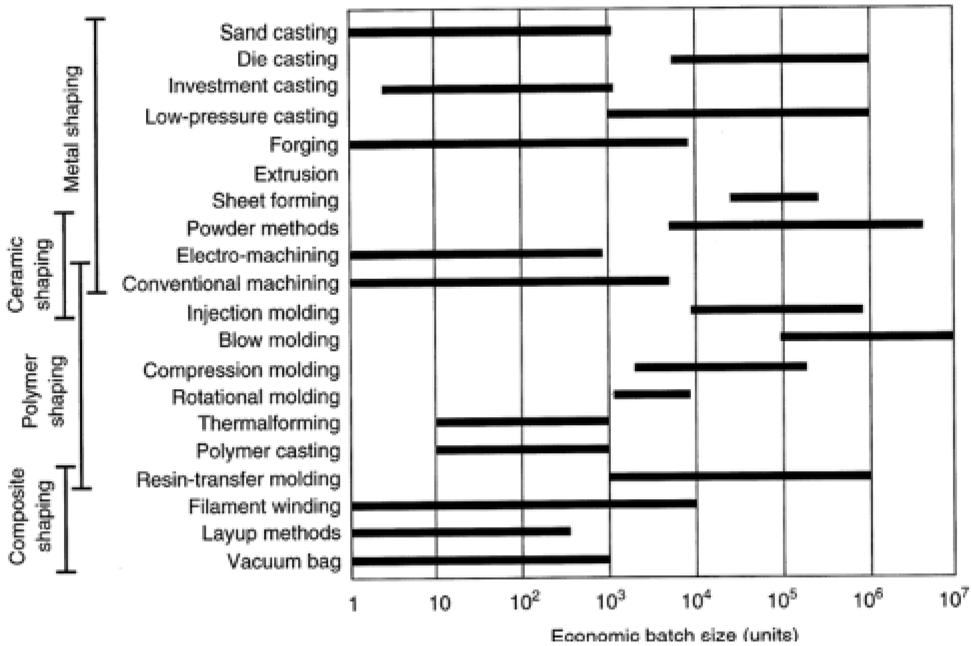
As the quantity of parts produced increases, the effect of fixed costs on unit cost decreases exponentially, while the effect of variable costs remains constant. Processes with high fixed costs but low variable costs can therefore be more cost effective for higher quantities. The figure and tables below provide useful examples of this phenomenon.



Process	Mold cost	Labor input/unit
Injection molding	$450,000	3 min = $1
Reaction injection molding	$90,000	6 min = $2
Compression molding	$55,000	6 min = $2
Contact molding	$20,000	1 h = $20

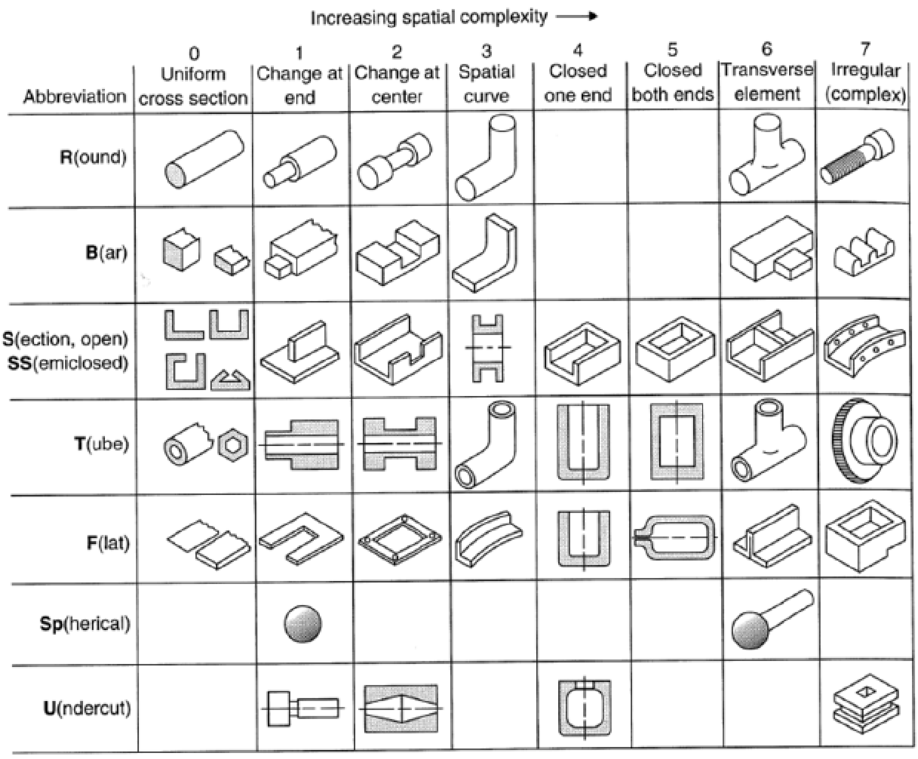
	Cost per part			
Process	1000 parts	10,000 parts	100,000 parts	1,000,000 parts
Injection molding	$451	$46	$5.50	$1.45
Reaction injection molding	$92	$11	$2.90	$2.09
Compression molding	$57	$7.50	$2.55	$2.06
Contact molding	$40	$22	$20.20	$20.02

For this reason, at each quantity of production some manufacturing processes are much more expensive than their alternatives. Given a desired quantity of parts to produce, we can therefore immediately narrow the range of manufacturing methods we will consider. The manufacturing process selection chart below indicates which methods are cost effective at which quantities.



Feature Complexity

Some manufacturing processes either cannot be used or are prohibitively expensive to use to form some types of shapes. These relationships are provided for several common manufacturing processes in the chart on the next page. This chart is organized by overall shape on the y axis and overall complexity on the x axis. Complexity might be characterized by the information content of a shape, i.e. the number of qualitative relationships or dimensions needed to describe it. With increasing complexity, fewer manufacturing processes are available and cost increases.

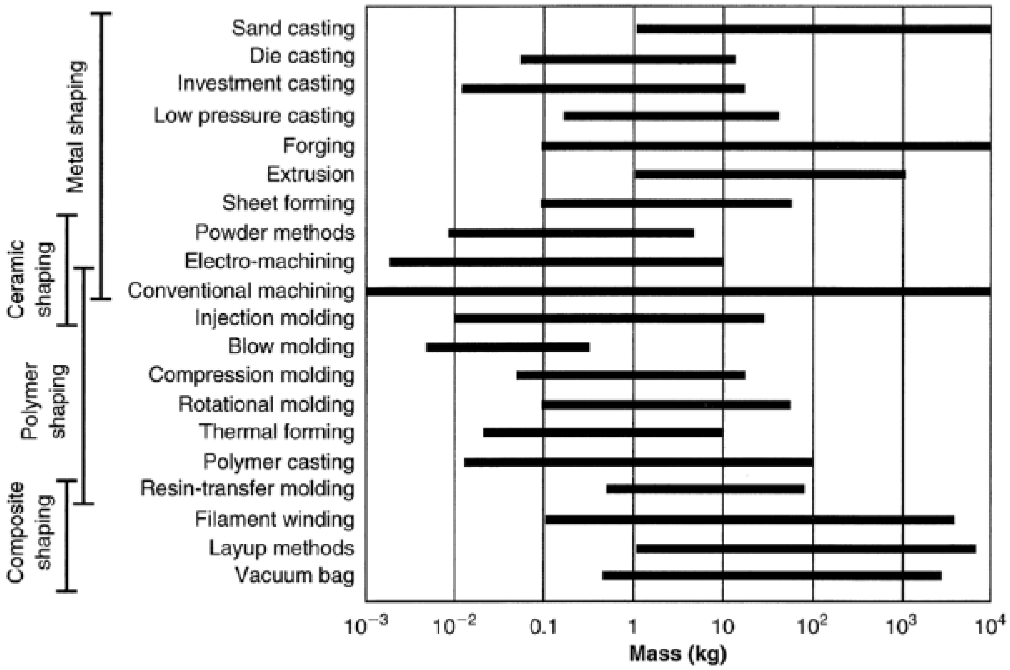


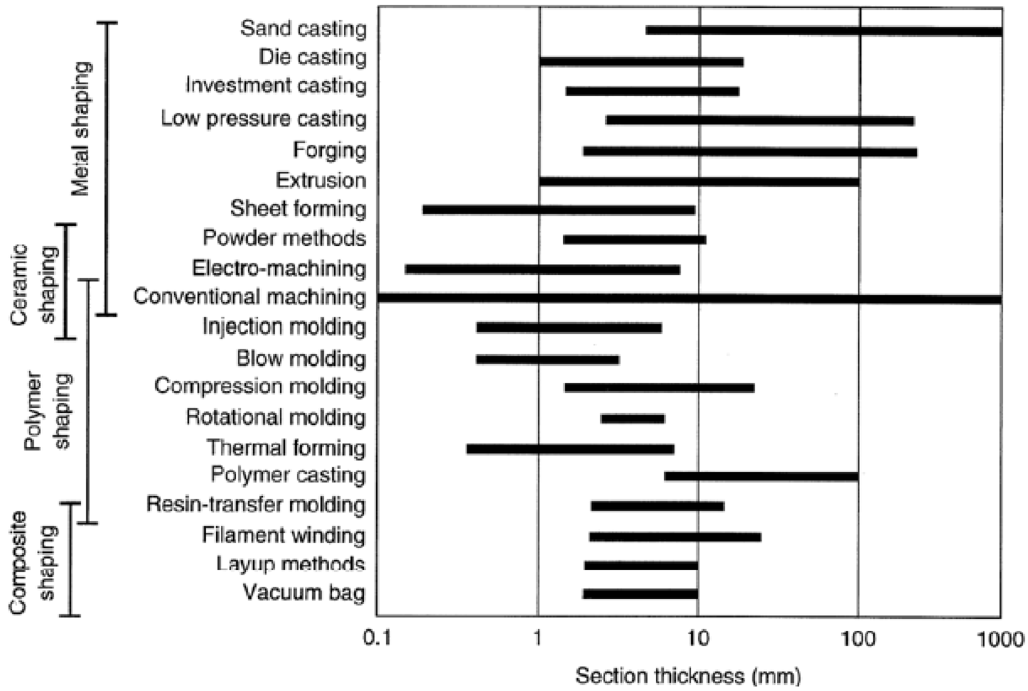
Ability of Manufacturing Processes to Produce Shapes in Fig. 13.6

Process	Capability for producing shapes
Casting processes	
Sand casting	Can make all shapes
Plaster casting	Can make all shapes
Investment casting	Can make all shapes
Permanent mold	Can make all shapes except T3, T5; F5; U1, U5, U7
Die casting	Same as permanent mold casting
Deformation processes	
Open-die forging	Best for R0 to R3; all B shapes; T1; F0; Sp6
Hot impression die forging	Best for all R, B, and S shapes; T1, T2; Sp
Hot extrusion	All 0 shapes
Cold forging/ cold extrusion	Same as hot die forging or extrusion
Shape drawing	All 0 shapes
Shape rolling	All 0 shapes
Sheet-metal working processes	
Blanking	F0 to F2; T7
Bending	R3; B3; S0, S2, S7; T3; F3, F6,
Stretching	F4; S7
Deep drawing	T4; F4, F7
Spinning	T1, T2, T4, T6; F4, F5

Part Size

Similarly, the size of parts to be produced also limits the set of economically viable manufacturing processes. In particular, overall size and section thickness are important in mass manufacturing. **Overall size** may imply a required workspace for a fabrication tool or a volume of material to cool from liquid form. In many molding processes, liquids are injected under pressure, and so the total surface area implies a die force that must be applied to keep the mold together. **Section thickness** refers to the smallest dimension of a component feature, e.g. a wall thickness. If a part is designed with a very thin feature, viscous materials may not be able to flow into the mold, may prematurely set, or may bead due to surface tension. If a part is designed with a very thick feature, by contrast, this can lead to very long cooling times in casting or molding processes. These size parameters therefore make some methods prohibitively expensive for smaller or larger components. These relationships are summarized in the manufacturing selection charts below.





Materials

Material properties can also affect the suitability of manufacturing processes. The table below is a complex, but relatively comprehensive, catalog of material types, quantities, and candidate manufacturing processes.

MATERIAL / QUANTITY	IRONS	STEEL (carbon)	STEEL (tool, alloy)	STAINLESS STEEL	COPPER & ALLOYS	ALUMINIUM & ALLOYS	MAGNESIUM & ALLOYS	ZINC & ALLOYS	TIN & ALLOYS	LEAD & ALLOYS	NICKEL & ALLOYS	TITANIUM & ALLOYS	THERMOPLASTICS	THERMOSETS	FR COMPOSITES	CERAMICS	REFRACTORY METALS	PRECIOUS METALS
VERY LOW 1 TO 100	[1.5] [1.6] [1.7] [4.M]	[1.5] [1.7] [3.10] [4.M] [5.1] [5.5] [5.6]	[1.1] [1.5] [1.7] [3.10] [4.M] [5.1] [5.5] [5.6] [5.7]	[1.6] [1.7] [3.7] [3.10] [4.M] [5.1] [5.5] [5.6]	[1.5] [1.7] [3.6] [4.M] [5.1]	[1.5] [1.7] [3.7] [3.10] [4.M] [5.5]	[1.6] [1.7] [3.10] [4.M] [5.1][5.5]	[1.1] [1.7] [3.10] [4.M] [5.5]	[1.1] [1.7] [3.10] [4.M] [5.5]	[1.1] [3.10] [4.M] [5.5]	[1.5] [1.7] [3.10] [4.M] [5.1] [5.5] [5.6]	[1.1] [1.6] [3.7] [3.10] [4.M] [5.1] [5.5] [5.6] [5.7]	[2.5] [2.7]	[2.5] [3.7]	[2.2] [2.6] [5.7]	[1.5] [5.1] [5.5] [5.6] [5.7]	[1.1] [5.7]	[5.5]
LOW 100 TO 1,000	[1.2] [1.5] [1.6] [1.7] [4.M] [5.3] [5.4]	[1.2] [1.6] [1.7] [1.10] [4.M] [5.1] [5.3] [5.4] [5.5]	[1.1] [1.2] [1.7] [4.M] [5.1] [5.3] [5.4] [5.5] [5.6] [5.7]	[1.2] [1.7] [3.7] [3.10] [4.M] [5.1] [5.3] [5.4] [5.5]	[1.2] [1.3] [1.5] [1.7] [1.8] [3.3] [3.6] [4.M] [5.1] [5.3] [5.4]	[1.2] [1.5] [1.7] [1.8] [3.7] [3.10] [4.M] [5.3] [5.4] [5.5]	[1.6] [1.7] [1.8] [3.10] [4.M] [5.5]	[1.1] [1.7] [1.8] [3.10] [4.M] [5.5]	[1.1] [1.7] [1.8] [3.10] [4.M] [5.5]	[1.1] [1.8] [3.10] [4.M] [5.5]	[1.2] [1.5] [1.7] [3.10] [4.M] [5.1] [5.3] [5.4] [5.5] [5.6]	[1.1] [1.6] [3.7] [3.10] [4.M] [5.1] [5.3] [5.4] [5.5] [5.6] [5.7]	[2.3] [2.5] [2.7]	[2.2] [2.3]	[2.2] [2.3] [2.6] [5.7]	[5.1] [5.3] [5.5] [5.6] [5.7]	[5.7]	[5.5]
LOW TO MEDIUM 1,000 TO 10,000	[1.2] [1.3] [1.5] [1.6] [1.7] [3.11] [4.A] [5.2]	[1.2] [1.3] [1.5] [1.7] [3.1] [3.3] [3.10] [3.11] [4.A] [5.2] [5.3] [5.4] [5.5]	[1.2] [1.5] [1.7] [3.1] [3.4] [3.11] [4.A] [5.2] [5.3] [5.4] [5.5]	[1.2] [1.5] [1.7] [3.1] [3.2] [3.7] [3.10] [3.11] [4.A.] [5.2] [5.3] [5.4] [6.0]	[1.2] [1.3] [1.5] [1.8] [3.1] [3.2] [3.10] [3.11] [4.A] [5.2] [5.3] [5.4]	[1.2] [1.3] [1.4] [1.5] [3.1] [3.3] [3.7] [3.10] [3.11] [4.A] [5.3] [5.4] [5.5]	[1.3] [1.5] [1.8] [3.1] [3.3] [3.4] [3.10] [4.A] [5.5]	[1.3] [1.8] [3.3] [3.10] [4.A] [5.5]	[1.3] [1.5] [3.2] [3.10]	[1.3] [1.5] [3.3] [3.10]	[1.2] [1.3] [1.5] [1.7] [3.1] [3.2] [3.11] [4.A] [5.1] [5.3] [5.4] [5.5] [3.10]	[3.1] [3.7] [3.10] [3.11] [4.A] [5.2] [5.3] [5.4] [5.5]	[2.3] [2.5] [2.6] [2.7]	[2.2] [2.3] [2.4]	[2.1] [2.2] [2.3]	[5.2] [5.3] [5.4] [5.5]		[5.5]
MEDIUM TO HIGH 10,000 TO 100,000	[1.2] [1.3] [3.11] [4.A]	[1.0] [2.1] [3.3] [3.4] [3.5] [3.11] [3.12] [4.A] [5.2] [5.5]	[3.1] [3.4] [3.5] [3.11] [3.12] [4.A] [5.2]	[1.0] [3.1] [3.3] [3.4] [3.5] [3.11] [3.12] [4.A]	[1.2] [1.4] [1.8] [3.1] [3.3] [3.4] [3.5] [3.11] [3.12] [4.A]	[1.2] [1.3] [1.4] [1.8] [3.1] [3.3] [3.4] [3.5] [3.11] [3.12] [4.A] [5.5]	[1.3] [1.4] [3.1] [3.3] [3.4] [3.5] [3.12] 4.A]	[1.3] [1.4] [3.3] [3.4] [3.5] [3.12] [4.A]	[1.3] [1.4] [3.3] [3.4] [3.12]	[1.3] [1.4] [3.3] [3.4] [3.8] [3.12] [4.A]	[3.1] [3.3] [3.5] [3.4] [3.11] [3.12] [4.A] [5.2] [5.5]	[3.1] [3.4] [3.11] [3.12] [4.A] [5.2] [5.5]	[2.1] [2.3] [2.6] [2.7] [2.8]	[2.1] [2.3] [2.9]	[2.1] [2.3]	[3.11]	[3.12]	[3.5]
HIGH 100,000+	[1.2] [1.3] [3.11] [4.A]	[1.9] [3.1] [3.2] [3.3] [3.4] [3.5] [3.12] [4.A]	[4.A]	[1.9] [3.2] [3.3] [4.A]	[1.2] [1.M] [3.1] [3.2] [3.3] [3.4] [3.5] [3.7] [3.8] [3.11] [3.12] [4.A]	[1.2] [1.3] [1.4] [1.6] [3.1] [3.2] [3.3] [3.4] [3.5] [3.8] [3.12] [4.A]	[1.3] [1.4] [3.1] [3.3] [3.4] [3.8] [3.12] [4.A]	[1.4] 3.2] [3.3] 3.4] [3.5] 4.A]	[1.4] [3.3] [3.4] [4.A]	[1.4] [3.2] [3.3] [3.4] [4.A]	[3.2] [3.3] [4.A]	[4.A]	[2.1] [2.6] [2.8]	[2.1] [2.3] [2.4] [2.9]		[3.7] [3.11]		[3.5]
ALL QUANTITIES	[1.1]	[1.1] [1.5] [3.0] [3.0] [3.0]	[1.6] [3.6]	[1.1] [1.6] [3.6] [3.8] [3.9]	[1.1] [1.6] [3.6] [3.8] [3.9] 5.5]	[1.1] [1.6] [3.4] [3.5] [3.6]	[1.1] [3.5] [3.6] [3.8]	[3.6] [3.8] [3.9]		[3.5]	[1.1] [1.6] [3.4] [3.5] [3.8]	[3.8] [3.9]				[5.5]	[1.5]	[1.6]

KEY TO MANUFACTURING PROCESS PRIMA SELECTION MATRIX:

CASTING PROCESSES
[1.1] SAND CASTING
[1.2] SHELL MOULDING
[1.3] GRAVITY DIE CASTING
[1.4] PRESSURE DIE CASTING
[1.5] CENTRIFUGAL CASTING
[1.6] INVESTMENT CASTING
[1.7] CERAMIC MOULD CASTING
[1.8] PLASTER MOULD CASTING
[1.9] SQUEEZE CASTING

PLASTIC & COMPOSITE PROCESSING
[2.1] INJECTION MOULDING
[2.2] REACTION INJECTION MOULDING
[2.3] COMPRESSION MOULDING
[2.4] TRANSFER MOULDING
[2.5] VACUUM MOULDING
[2.6] BLOW MOULDING
[2.7] ROTATIONAL MOULDING
[2.8] CONTACT MOULDING
[2.9] CONTINUOUS EXTRUSION (PLASTICS)

FORMING PROCESSES
[3.1] CLOSED DIE FORGING
[3.2] ROLLING
[3.3] DRAWING
[3.4] COLD FORMING
[3.5] COLD HEADING
[3.6] SWAGING
[3.7] SUPERPLASTIC FORMING
[3.8] SHEET-METAL SHEARING
[3.9] SHEET-METAL FORMING
[3.10] SPINNING
[3.11] POWDER METALLURGY
[3.12] CONTINUOUS EXTRUSION

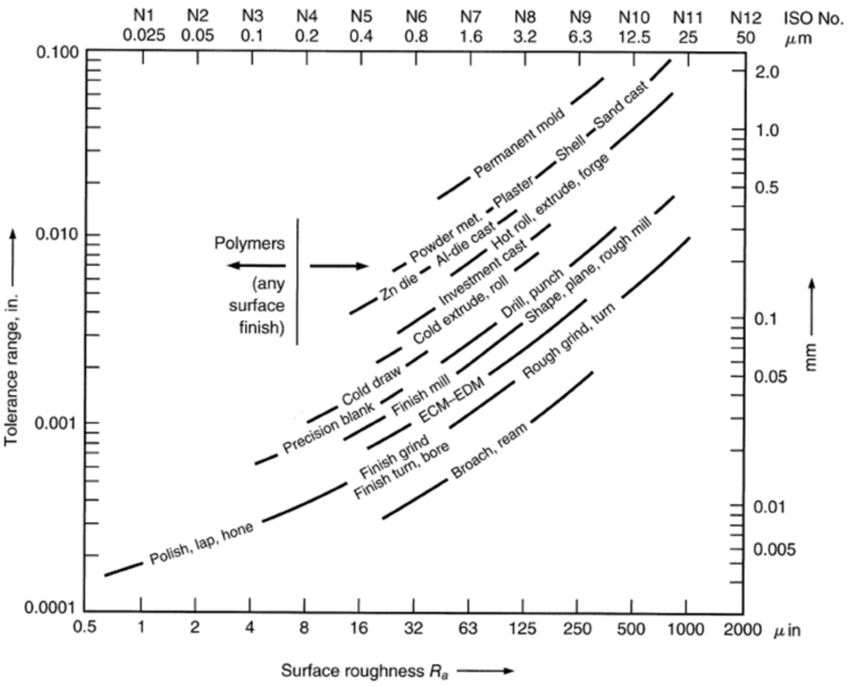
MACHINING PROCESSES
[4.A] AUTOMATIC MACHINING
[4.M] MANUAL MACHINING

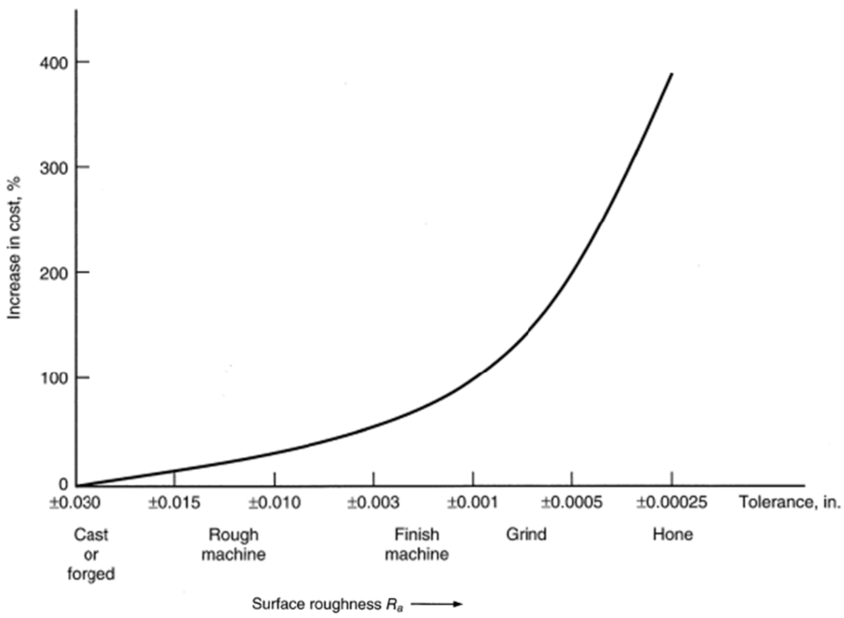
(THE ABOVE HEADINGS COVER A BROAD RANGE OF MACHINING PROCESSES AND LEVELS OF CONTROL TECHNOLOGY. FOR MORE DETAIL, THE READER IS REFERRED TO THE INDIVIDUAL PROCESSES.)

NTM PROCESSES
[5.1] ELECTRICAL DISCHARGE MACHINING (EDM)
[5.2] ELECTROCHEMICAL MACHINING (ECM)
[5.3] ELECTRON BEAM MACHINING (EBM)
[5.4] LASER BEAM MACHINING (LBM)
[5.5] CHEMICAL MACHINING (CM)
[5.6] ULTRASONIC MACHINING (USM)
[5.7] ABRASIVE JET MACHINING (AJM)

Required Quality

Manufacturing process choice will effect part quality in terms of overall dimensional tolerance or surface condition, with increased quality correlated with increased unit cost. These relationships are approximated below.





10.1 Acknowledgments

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