Chapter 12

Case studies: process selection

12.1 Introduction and synopsis

The previous chapter described a systematic procedure for process selection. The inputs are design requirements; the output is a shortlist of processes capable of meeting them. The case studies of this chapter illustrate the method. The first four make use of hard-copy charts; the last two show how computer-based selection works. More details for each are then sought, starting with the texts listed under Further reading for Chapter 11, and progressing to the specialized data sources described in Chapter 13. The final choice evolves from this subset, taking into account local factors, often specific to a particular company, geographical area or country.

The case studies follow a standard pattern. First, we list the *design requirements:* size, minimum section, surface area, shape, complexity, precision and finish, and the *material* and the *processing constraints* that it creates (melting point and hardness). Then we plot these requirements onto the process charts, identifying search areas. The processes which overlap the search areas are capable of making the component to its design specification: they are the candidates. If no one process meets all the design requirements, then processes have to be 'stacked': casting followed by machining (to meet the tolerance specification on one surface, for instance); or powder methods followed by grinding. Computer-based methods allow the potential candidates to be ranked, using economic criteria. More details for the most promising are then sought, starting with the texts listed under Further reading for Chapter 11, and progressing to the specialized data sources described in Chapter 13. The final choice evolves from this subset, taking into account local factors, often specific to a particular company, geographical area or country.

12.2 Forming a fan

Fans for vacuum cleaners are designed to be cheap, quiet and efficient, probably in that order. Case study 6.6 identified a number of candidate materials, among them, aluminium alloys and nylon. Both materials are cheap. The key to minimizing process costs is to form the fan to its final shape in a single operation — that is, to achieve net-shape forming — leaving only the central hub to be machined to fit the shaft with which it mates. This means the selection of a process which can meet the specifications on precision and tolerance, avoiding the need for machining or finishing of the disk or blades.

The design requirements

The pumping rate of a fan is determined by its radius and rate of revolution: it is this which determines its size. The designer calculates the need for a fan of radius 60mm, with 20 blades of

Table 12.1 Design constraints for the fan

Constraint	*Value*	
Materials	Nylons	$T_m = 550–573\,\text{K}$ $H = 150–270\,\text{MPa}$ $\rho = 1080\,\text{kg/m}^3$
	Al-alloys	$T_m = 860–933\,\text{K}$ $H = 150–1500\,\text{MPa}$ $\rho = 2070\,\text{kg/m}^3$
Complexity	2 to 3	
Min. Section	1.5–6 mm	
Surface area	$0.01–0.04\,\text{m}^2$	
Volume	$1.5 \times 10^{-5}–2.4 \times 10^{-4}\,\text{m}^3$	
Weight	0.03–0.5 kg	
Mean precision	± 0.5 mm	
Roughness	$< 1\,\mu\text{m}$	

average thickness 3 mm. The surface area, approximately $2(\pi R^2)$, is $2 \times 10^{-2}\,\text{m}^2$. The volume of material in the fan is, roughly, its surface area times its thickness — about $6 \times 10^{-5}\,\text{m}^3$, giving a weight in the range 0.03 (nylon) to 0.5 kg (aluminium). If formed in one piece, the fan has a fairly complex shape, though its high symmetry simplifies it somewhat. We classify it as 3-D solid, with a complexity between 2 and 3. In the designer's view, the surface finish is what really matters. It (and the geometry) determine the pumping efficiency of the fan and influence the noise it makes. He specifies a smooth surface: $R < 1\,\mu\text{m}$. The design constraints are summarized in Table 12.1.

What processes can meet them?

The selection

We turn first to the size–shape chart, reproduced as Figure 12.1. The surface area and minimum section define the search area labelled 'FAN' — it has limits which lie a factor 2 on either side of the target values. It shows that the fan can be shaped in numerous ways; they include *die-casting* for metals and *injection moulding* for polymers.

Turn next to the complexity–size chart, reproduced in Figure 12.2. The requirements for the fan again define a box. We learn nothing new: the complexity and size of the fan place it in a regime in which many alternative processes are possible. Nor do the material properties limit processing (Figure 12.3); both materials can be formed in many ways.

The discriminating requirement is that for smoothness. The design constraints $R < \pm 1\,\mu\text{m}$ and $T < 0.5$ mm are shown on Figure 12.4. Any process within the fan search region is a viable choice; any outside is not. Machining from solid meets the specifications, but is not a net-shape process. A number of polymer moulding processes are acceptable, among them, injection moulding. Few metal-casting processes pass — the acceptable choices are pressure die-casting, squeeze casting and investment casting.

The processes which pass all the selection steps are listed in Table 12.2. They include injection moulding for the nylon and die-casting for the aluminium alloy: these can achieve the desired shape, size, complexity, precision and smoothness, although a cost analysis (Case Study 12.5) is now needed to establish them as the best choices.

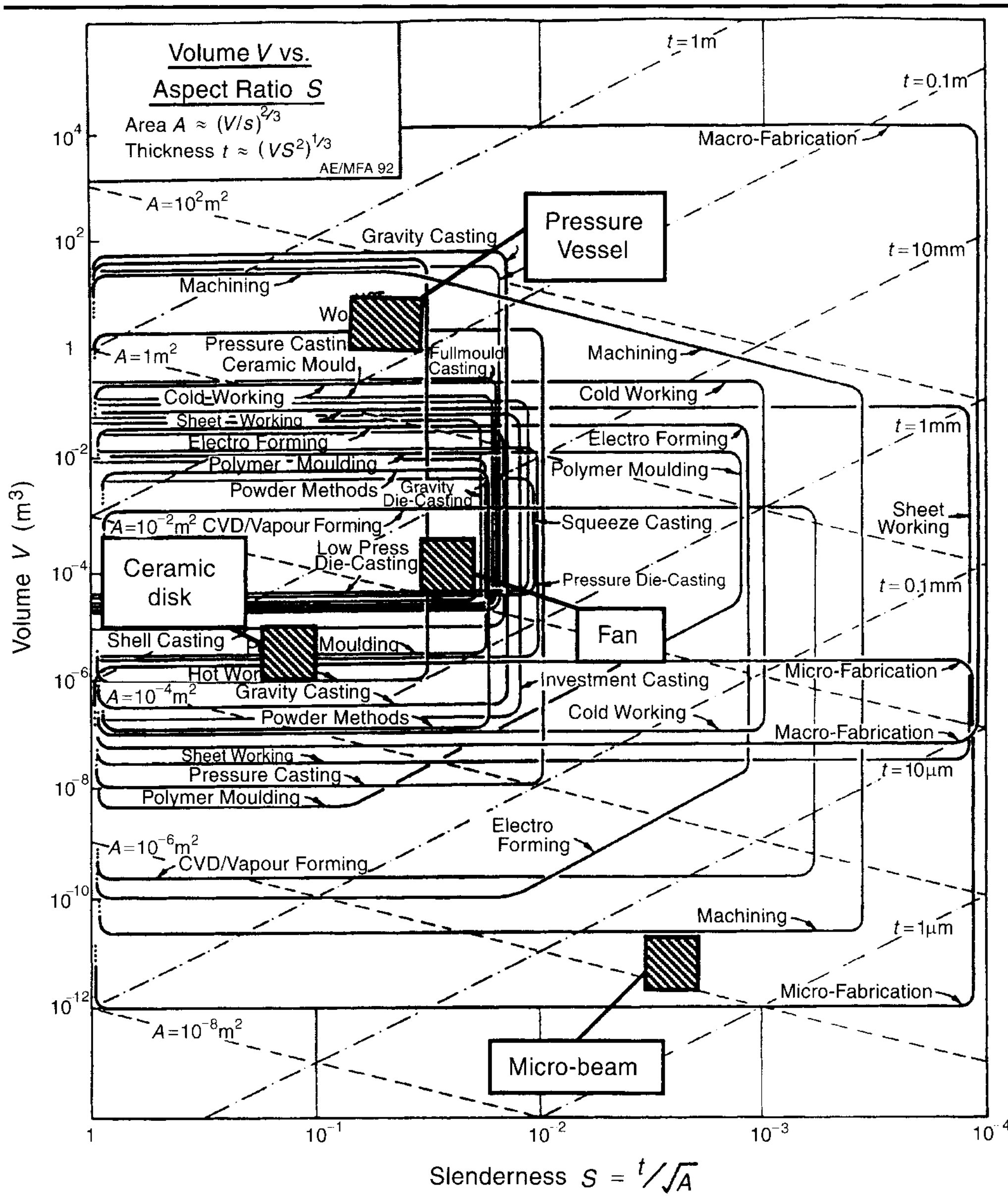

Fig. 12.1 The size–slenderness–area–thickness chart, showing the search areas for the fan, the pressure vessel, the micro-beam and the ceramic tap valve.

Postscript

There are (as always) other considerations. There are the questions of capital investment, batch size and rate, supply, local skills and so forth. The charts cannot answer these. But the procedure has been helpful in narrowing the choice, suggesting alternatives, and providing a background against which a final selection can be made.

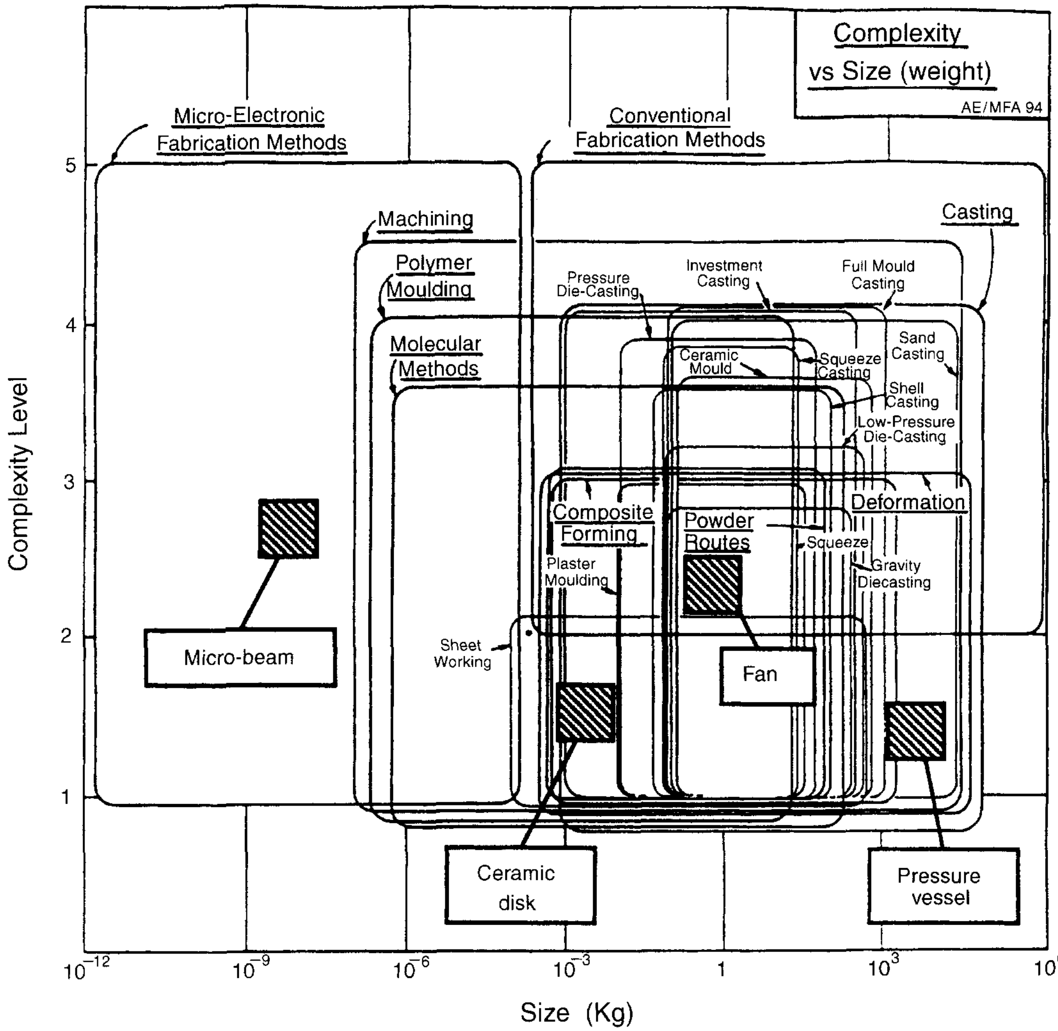

Fig. 12.2 The complexity–size chart, showing the search areas for the fan, the pressure vessel, the micro-beam and the ceramic tap valve.

Related case studies

Case Study 6.7: Materials for high flow fans
Case Study 14.3: Data for a non-ferrous alloy

12.3 Fabricating a pressure vessel

A pressure vessel is required for a hot-isostatic press or HIP (Figure 11.13). Materials for pressure vessels were the subject of Case Study 6.14; tough steels are the best choice.

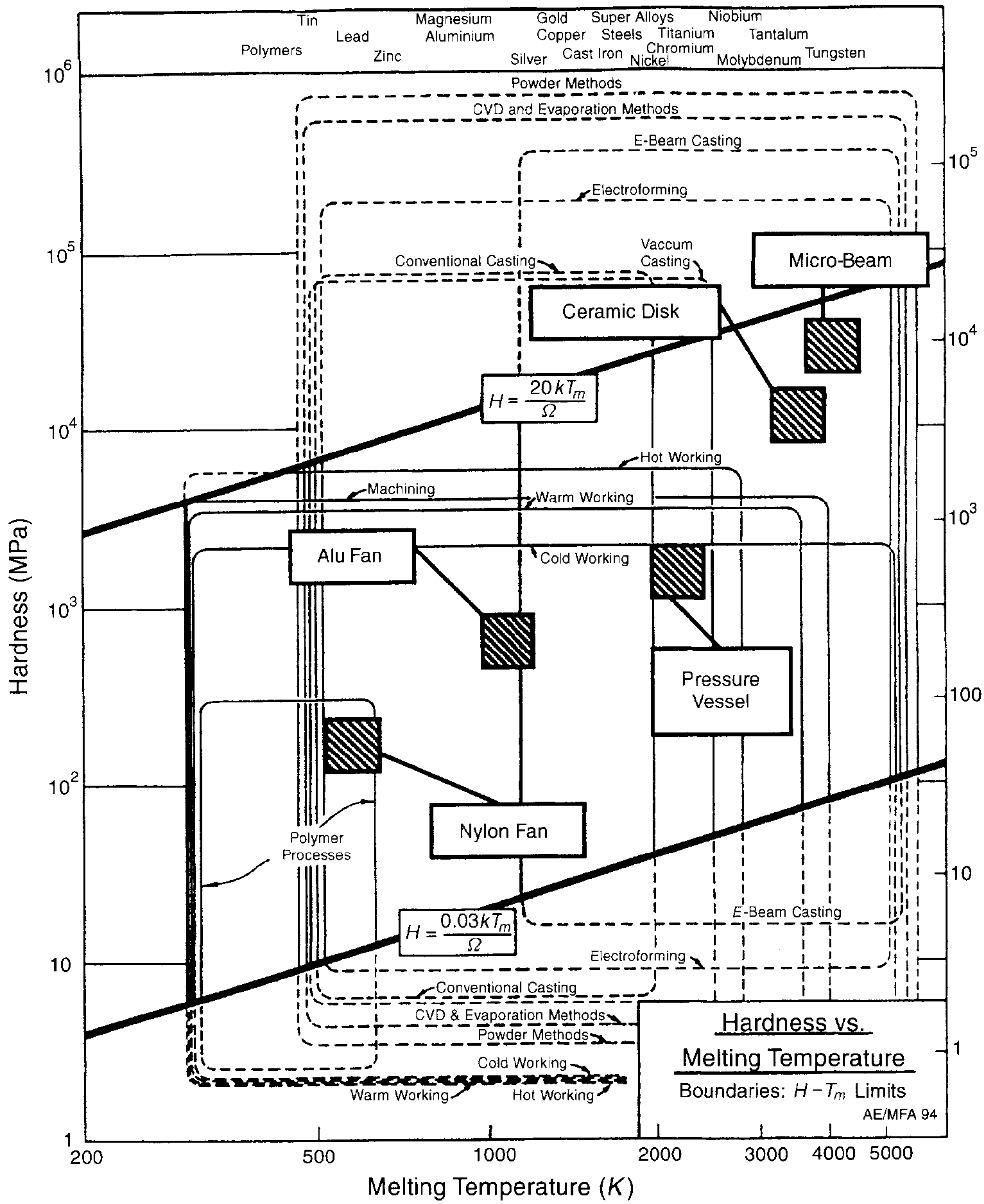

Fig. 12.3 The hardness–melting point chart, showing the search areas for the fan, the pressure vessel, the micro-beam and the ceramic tap valve.

The design requirements

The design asks for a cylindrical pressure vessel with an inside radius R_i of 0.5 m and a height h of 1 m, with removable end-caps (Figure 12.5). It must safely contain a pressure p of 100 MPa. A steel with a yield strength σ_y of 500 MPa (hardness: 1.5 GPa) has been selected. The necessary

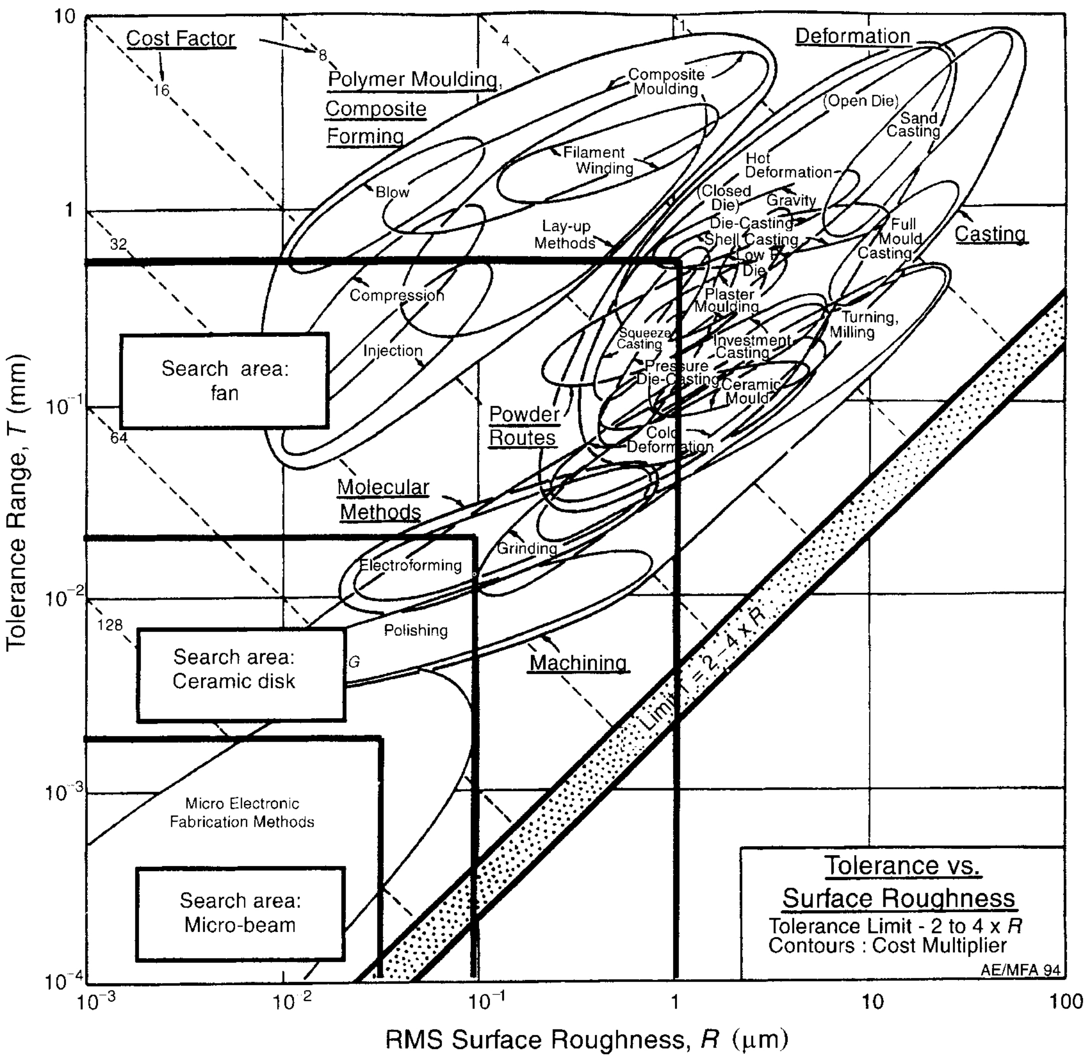

Fig. 12.4 The tolerance–roughness chart, showing the search areas for the fan, the micro-beam and the ceramic tap valve.

wall thickness t is given approximately by equating the hoop stress in the wall, roughly pR/t, to the yield strength of the material of which it is made, σ_y, divided by a safety factor S_f which we will take to be 2:

$$t = \frac{S_f pR}{\sigma_y} = 0.2\,\text{m} \tag{12.1}$$

The outside radius R_o is, therefore, 0.7 m. The surface area A of the cylinder (neglecting the end-caps) follows immediately: it is roughly 3.8 m^2. The volume $V = At$ is approximately 0.8 m^3. Lest that sounds small, consider the weight. The density of steel is just under 8000 kg/m^3. The vessel weighs 6 tonnes. The design constraints are shown at Table 12.3.

Table 12.2 Processes for forming the fan

Process	*Comment*
Machine from solid	Expensive. Not a net-shape process.
Electro-form	Slow, and thus expensive.
Cold deformation	Cold forging meets design constraints.
Investment casting	Accurate but slow.
Pressure die casting	Meets all design constraints.
Squeeze cast	Meets all design constraints.
Injection moulding	Meets all design constraints.
Resin transfer moulding	Meets all design constraints.

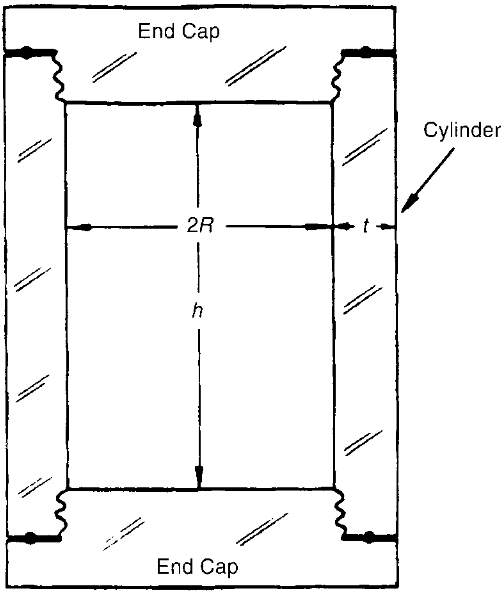

Fig. 12.5 Schematic of the pressure vessel of a hot isostatic press.

Table 12.3 Design constraints for the pressure vessel

Constraint	*Value*	
Material	Steel	$T_m = 1600\,K$ $H = 2000\,MPa$ $\rho = 8000\,kg/m^3$
Complexity	2	
Min. Section	200 mm	
Surface area	3.8 m^2	
Volume	0.8 m^3	
Weight	6000 kg	
Mean precision	± 1.0 mm	
Roughness	$<1\,\mu m$ on mating surfaces only	

A range of pressures is envisaged, centred on this one, but with inner radii and pressures which range by a factor of 2 on either side. (A constant pressure implies a constant 'aspect ratio', R/t.) Neither the precision nor the surface roughness of the vessel are important in selecting the primary forming operation because the end faces and internal threads will be machined, regardless of how it is made. What processes are available to shape the cylinder?

The selection

The discriminating requirement, this time, is size. The design requirements of wall thickness and surface area are shown as a labelled box on Figure 12.1. It immediately singles out the four possibilities listed in Table 12.4: the vessel can be machined from the solid, made by hot-working, cast, or fabricated (by welding plates together, for instance).

Complexity and size (Figure 12.2) confirm the choice. Material constraints are worth checking (Figure 12.3), but they do not add any further restrictions. Tolerance and roughness do not matter except on the end faces and threads (where the end-caps must mate) and any ports in the sides — these require high levels of both. The answer here (Figure 12.4) is to machine, and perhaps surface-grind.

Postscript

A 'systematic' procedure is one that allows a conclusion to be reached without prior specialized knowledge. This case study is an example. We can get so far (Table 12.4) systematically, and it is a considerable help. But we can get no further without adding some expertise.

A cast pressure vessel is not impossible, but it would be viewed with suspicion by an expert because of the risk of casting defects; safety might then require elaborate ultrasonic testing. The only way to make very large pressure vessels is to weld them, and here we encounter the same problem: welds are defect-prone and can only be accepted after elaborate inspection. Forging, or machining from a previously forged billet are the best because the large compressive deformation heals defects and aligns oxides and other muck in a harmless, strung-out way.

That is only the start of the expertise. You will have to go to an expert for the rest.

Related case studies

Case Study 6.15: Safe pressure vessels

Table 12.4 Processes for forming pressure vessels

Process	*Comment*
Machining	Machine from solid (rolled or forged) billet. Much material discarded, but a reliable product. Might select for one-off.
Hot working	Steel forged to thick-walled tube, and finished by machining end faces, ports, etc. Preferred route for economy of material use.
Casting	Cast cylindrical tube, finished by machining end-faces and ports. Casting-defects a problem.
Fabrication	Weld previously-shaped plates. Not suitable for the HIP; use for very large vessels (e.g. nuclear pressure vessels).

12.4 Forming a silicon nitride micro-beam

The ultimate in precision mechanical metrology is the atomic-force microscope; it can measure the size of an atom. It works by mapping, with Angström resolution, the forces near surfaces, and, through these forces, the structure of the surface itself. The crucial component is a micro-beam: a flexible cantilever with a sharp stylus at its tip (Figure 12.6). When the tip is tracked across the surface, the forces acting between it and the sample cause minute deflections of the cantilever which are detected by reflecting a laser beam off its back surface, and are then displayed as an image.

The design requirements

Albrecht and his colleagues (1990) list the design requirements for the micro-beam. They are: minimum thermal distortion, high resonant frequency, and low damping. If these sound familiar, it is perhaps because you have read Case Study 6.19: 'Materials to minimize thermal distortion in precision devices'. There, the requirements of minimum thermal distortion and high resonant frequency led to a shortlist of candidate materials: among them, silicon carbide and silicon nitride.

The demands of sensitivity require beam dimensions which range, by a factor of 2 (depending on material), about those shown in Figure 12.6. The minimum section, t, lies in the range 2 to 8 μm; the surface area is about $10^{-6}\,m^2$, the volume is roughly $5 \times 10^{-12}\,m^3$, and the weight approximately 10^{-8} kg.

Precision is important in a device of this sort. The precision of 1% on a length of order 100 mm implies a tolerance of ±1 μm. Surface roughness is only important if it interferes with precision, requiring $R < 0.04$ μm.

The candidate materials — silicon carbide and silicon nitride — are, by this time, part of the design specification. They both have very high hardness and melting points. Table 12.5 summarizes the design constraints.

How is such a beam to be made?

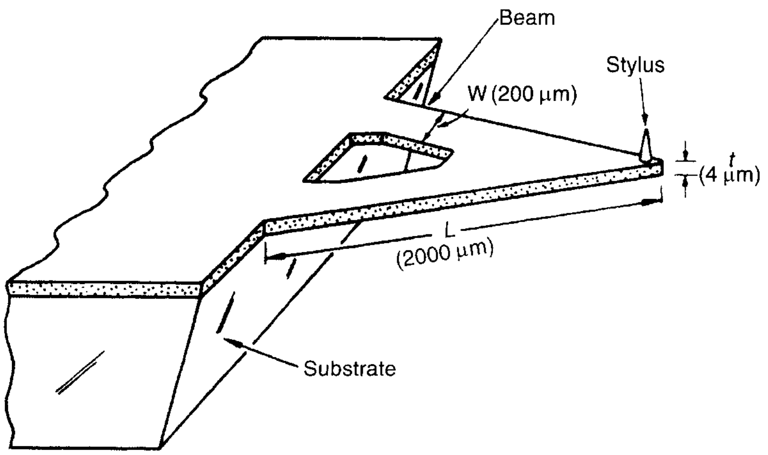

Fig. 12.6 A micro-beam for an atomic-force microscope.

Table 12.5 Design constraints for the micro-beam

Constraint		*Value*
Materials	Silicon carbide	$T_m = 2973$–$3200\,\mathrm{K}$ $H = 30\,000$–$33\,000\,\mathrm{MPa}$
	Silicon nitride	$T_m = 2170$–$2300\,\mathrm{K}$ $H = 30\,000$–$34\,000\,\mathrm{MPa}$
Complexity	2 to 3	
Min. section	2–8 μm	
Surface area	5×10^{-7}–$2 \times 10^{-6}\,\mathrm{m}^2$	
Volume	2×10^{-12}–$10^{-11}\,\mathrm{m}^3$	
Weight ($\rho = 3000\,\mathrm{kg/m}^3$)	6×10^{-9}–$3 \times 10^{-8}\,\mathrm{kg}$	
Mean precision	±0.5 to 1 μm	
Roughness	<0.04 μm	

The selection

The section and surface area locate the beam on Figure 12.1 in the position shown by the shaded box. It suggests that it may be difficult to shape the beam by conventional methods, but that the methods of micro-fabrication could work. The conclusion is reinforced by Figure 12.2.

Material constraints are explored with the hardness–melting point chart of Figure 12.3. Processing by conventional casting or deformation methods is impossible; so is conventional machining. Powder methods can shape silicon carbide and nitride, but not, Figure 12.3 shows, to anything like the size or precision required here. The CVD and evaporation methods of micro-fabrication look like the best bet.

The dimensions, precision, tolerance and finish all point to micro-fabrication. Silicon nitride can be grown on silicon by gas-phase techniques, standard for micro-electronics. Masking by lithography, followed by chemical 'milling' — selective chemical attack — allows the profile of the beam to be cut through the silicon nitride. A second chemical process is then used to mill away the underlying silicon, leaving the cantilever of silicon nitride meeting the design specifications.

Postscript

Cantilevers with length as small as 100 μm and a thickness of 0.5 μm have been made successfully by this method — they lie off the bottom of the range of the charts. The potential of micro-fabrication for shaping small mechanical components is considerable, and only now being explored.

Related case studies

Case Study 6.20: Materials to minimize thermal distortion in precision devices

12.5 Forming ceramic tap valves

Vitreous alumina, we learn from Case Study 6.20, may not be the best material for a hot water valve — there is evidence that thermal shock can crack it. Zirconia, it is conjectured, could be better. Fine. How are we to shape it?

The design requirements

Each disc of Figure 6.36 has a diameter of 20 mm and a thickness of 5 mm (surface area $\approx 10^{-3}$ m^2; volume 1.5×10^{-6} m^3). They have certain obvious design requirements. They are to be made from zirconia, a hard, high-melting material. Their mating surfaces must be flat and smooth so that they seal well. The specifications for these surfaces are severe: $T \leq \pm 20\,\mu$m, and $R < 0.1\,\mu$m. The other dimensions are less critical (constraints are shown in Table 12.6). Any process which will form zirconia to these requirements will do. There aren't many.

The selection

The size is small and the shape is simple: they impose no great restrictions (Figures 12.1 and 12.2). It is the material which is difficult. Its melting point is high (2820 K or 2547°C) and its hardness is too (15 GPa). The chart we want is that of hardness and melting point. The search region for zirconia is shown on Figure 12.3. It identifies a subset of processes, listed in the first column of Table 12.7. Armed with this list, standard texts reveal the further information given in the second column. Powder methods emerge as the only practical way to make the discs.

Powder methods can make the shape, but can they give the tolerance and finish? Figure 12.3, shows that they cannot. The mating face of the disc will have to be ground and polished to give the desired tolerance and smoothness.

Postscript

Here, as in the earlier case studies, the design requirements alone lead to an initial shortlist of processes. Further, detailed, information for these must then be sought. The texts on processing

Table 12.6 Design constraints for the valve

Constraint	*Value*
Materials	Zirconia $T_m = 2820$ K $H = 15\,000$ MPa
Complexity	1–2
Min. Section	5 mm
Surface area	10^{-3} m^2
Volume	1.5×10^{-6} m^3
Weight ($\rho = 3000$ kg/m^3)	4.5×10^{-3} kg
Mean precision	± 0.02 mm
Roughness	$<0.1\,\mu$m

Table 12.7 Processes for shaping the valve

Process	*Comment*
Powder methods	Capable of shaping the disc, but not to desired precision.
CVD and Evaporation methods	No CVD route available. Other gas-phase methods possible for thin sections.
Electron-beam casting	Difficult with a non-conductor.
Electro-forming	Not practical for an oxide.

(Further reading of Chapter 11) and the material-specific data sources (Chapters 13 and 14) almost always suffice.

Related case studies

Case Study 6.21: Ceramic valves for taps
Case Study 14.5: Data for a ceramic

12.6 Economical casting

Optical benches are required for precision laser-holography. The list of materials thrown up as candidates for precision devices (Case Study 6.20) included aluminium and its alloys. The decision has been taken to cast the benches from Alloy 380, an aluminium–silicon alloy developed for casting purposes (Case Study 14.3).

The design requirements

The designer, uncertain of the market for the benches, asks for advice on the best way to cast one prototype bench, a preliminary run of 100 benches, and (if these succeed) enough benches to satisfy a potential high-school market of about 10 000. The high precision demanded by the design can only be met by machining the working surfaces of the bench, so the tolerance and roughness of the casting itself do not matter. The best choice of casting method is the cheapest.

Process data for four possible casting methods for aluminium alloys are listed in Table 12.8. The costs are given in units of the material cost, C_m, of one bench (that is, $C_m = 1$). In these units, labour costs, C_L , are 20 units per hour. Estimates for the capital cost C_c of setting up each of the four processes come next. Finally, there is the batch rate for each process, in units per hour. Which is the best choice?

The selection

Provided the many components of cost have been properly distributed between C_m, C_L and C_c, the cost of manufacturing one bench is (equation (11 .7))

$$C = C_m + \frac{C_C}{n} + \frac{C_L}{\dot{n}}$$

where n is the batch size and $\dot{n}$ the batch rate. Analytical solutions for the cheapest process are possible, but the most helpful way to solve the problem is by plotting the equation for each of the four casting methods using the data in Table 12.8. The result is shown in Figure 12.7.

Table 12.8 Process costs for four casting methods

Process	*Sand casting*	*Low pressure*	*Permanent mould*	*Die casting*
Material, C_m	1	1	1	1
Labour, C_L (h^{-1})	20	20	20	20
Capital, C_c	0.9	4.4	700	3000
Rate $\dot{n}$ (h^{-1})	6.25	22	10	50

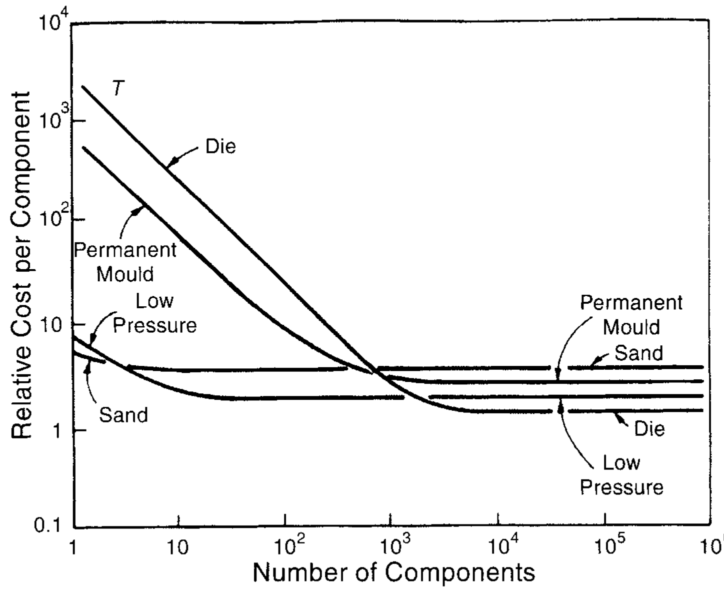

Fig. 12.7 The unit cost/batch size graph for the four casting processes for aluminium alloys.

The selection can now be read off: for one bench, sand casting is marginally the cheapest. But since a production run of 100 is certain, for which low-pressure casting is cheaper, it probably makes sense to use this for the prototype as well. If the product is adopted by schools, die casting becomes the best choice.

Postscript

All this is deceptively easy. The difficult part is that of assembling the data of Table 12.8, partitioning costs between the three heads of material, labour and capital. In practice this requires a detailed, in-house, study of costs and involves information not just for the optical bench but for the entire product line of the company. But when — for a given company — the data for competing processes are known, selecting the cheapest route for a new design can be guided by the method.

Related case studies

Case Study 6.20: Materials to minimize thermal distortion in precision instruments
Case Study 14.3: Data for a non-ferrous alloy

12.7 Computer-based selection — a manifold jacket

The difficulties of using hard-copy charts for process selection will, by now, be obvious: the charts are too cluttered, the overlap too great. They give a helpful overview but they are not the way to get a definitive selection. Computer-based methods increase the resolution.

A computer-based selector (*CPS* 1998) which builds on the method of Chapter 11 is illustrated below. Its database consists of a number of records each containing data for the attributes of one process. These include its *physical attributes* (the ranges of size, tolerance, precision, etc.) and its *economic attributes* (economic batch size, equipment and tooling cost, production rate and so forth). A *material-class menu* allows selection of the subset of process which can shape a given material; a *shape-class menu* allows selection shape (continuous or discrete, prismatic, sheet, 3-D solid, 3-D hollow and the like); and a *process-class menu* allows the choice of process type (primary, secondary, tertiary, etc.).

The best way to use the selector is by creating a sequence of charts with a class attribute on one axis and a physical or economic attribute on the other; superimposed selection boxes define the design requirements, as in Case Studies 12.1 to 12.4. A choice of *Size Range* plotted for processes for which *Material Class* = *Ferrous Metals*, for instance, gives a bar-chart with bars showing the range of size which lies within the capacity of process which can shape ferrous metals. A selection box positioned to bracket the Size Range between 10 and 15 kg then isolates the subset of processes which can shape ferrous metals to this particular size. The procedure is repeated to select shape, process type, tolerance, economic batch size, and more if required. The output is the subset of processes which satisfy *all* the requirements.

This case study and the next will show how the method works.

The design requirements

The manifold jacket shown in Figure 12.8 is part of the propulsion system of a space vehicle. It is to be made of nickel. It is large, weighing about 7 kg, and very complicated, having a 3D-hollow shape with transverse features and undercuts. The minimum section thickness is between 2 and 5 mm. The requirement on precision is strict (tolerance $< \pm 0.1$ mm). Because of its limited application, only 10 units are to be made. Table 12.9 lists the requirements.

The selection

The output of a computer-based process selector (*CPS*, 1998) is shown in Figures 12.9–12.12. Figure 12.9 shows the first of the selection stages: a bar chart of *mass range* against material class, choosing *non-ferrous metal* from the menu of material classes. The selection box brackets a mass

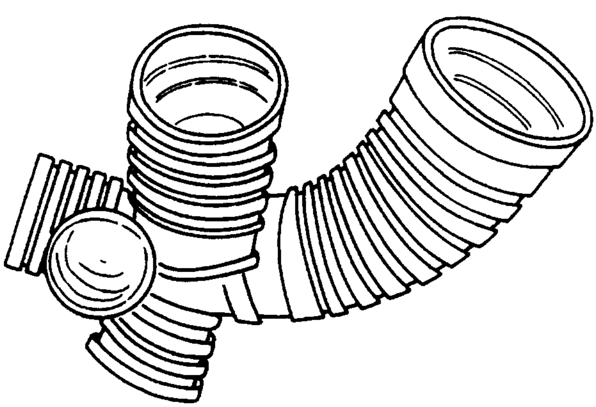

Fig. 12.8 A manifold jacket (source: Bralla, 1986).

Table 12.9 Design requirements for the manifold jacket

Constraint	*Value*
Material class	Non-ferrous metal: nickel
Process class	Primary, discrete
Shape class	3-D hollow, transverse features
Weight ($\rho = 3000\,kg/m^3$)	7 kg
Min. section	2 to 5 mm
Tolerance	$< \pm 0.1$ mm
Roughness	$<10\,\mu m$
Batch size	10

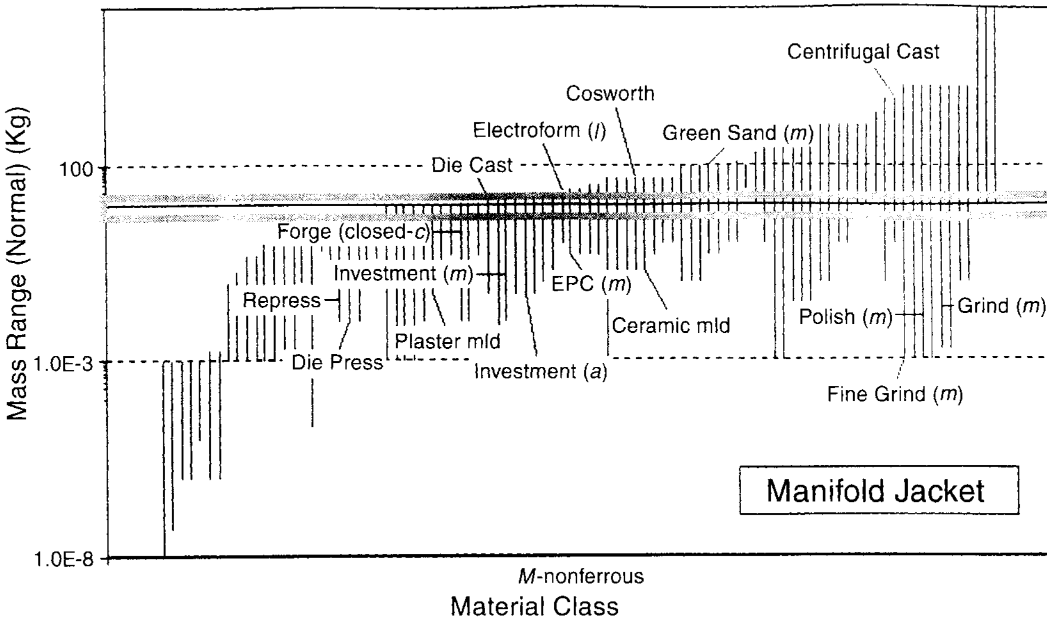

Fig. 12.9 A chart of mass range against material class. The box isolates processes which can shape non-ferrous alloys and can handle the desired mass range.

range of 5–10 kg. Many processes pass this stage, though, of course, all those which cannot deal with non-ferrous metals have been eliminated.

We next seek the subset of processes which can produce the complex shape of the manifold and the desired section thickness, creating a chart of *minimum section thickness* for shapes with *3D-hollow-transverse features*, selected from the menu of shape classes (Figure 12.10). The selection box encloses thicknesses in the range 2 to 5 mm. Again, many processes pass, although any which cannot produce the desired shape fail.

The third selection stage, Figure 12.11, is a bar-chart of *tolerance* against process class selecting *primary processes* (one which creates a shape, rather than one which finishes or joins) from the process class menu. The selection box specifies the tolerance requirement of ± 0.1 mm or better. Very few processes can achieve this precision.

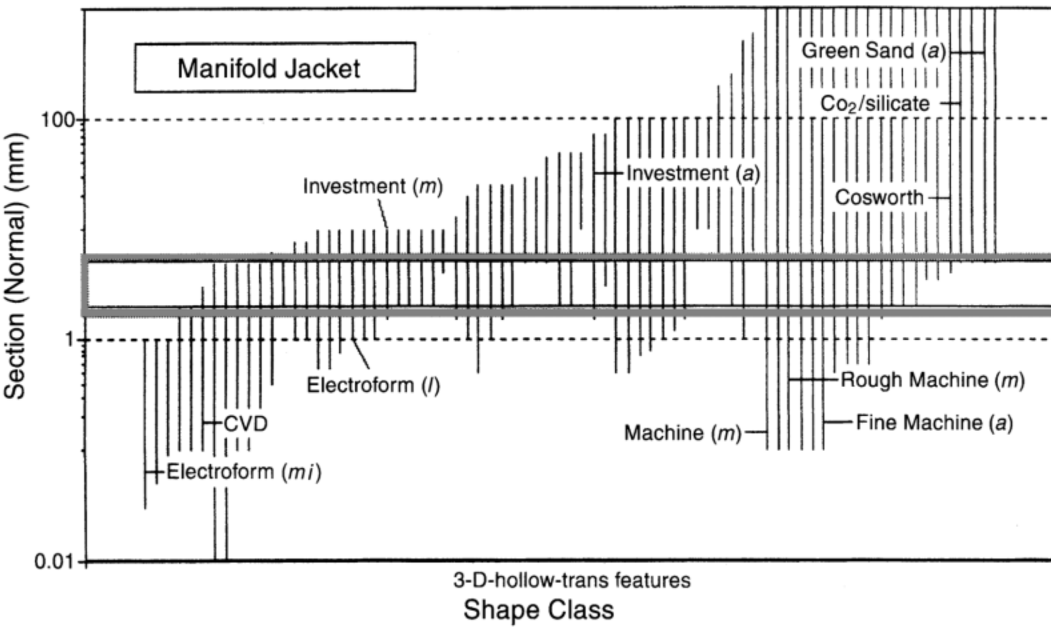

Fig. 12.10 A chart of section thickness range against shape class. The chart identifies processes capable of making 3D-hollow shapes having transverse features with sections in the range 2-5 mm.

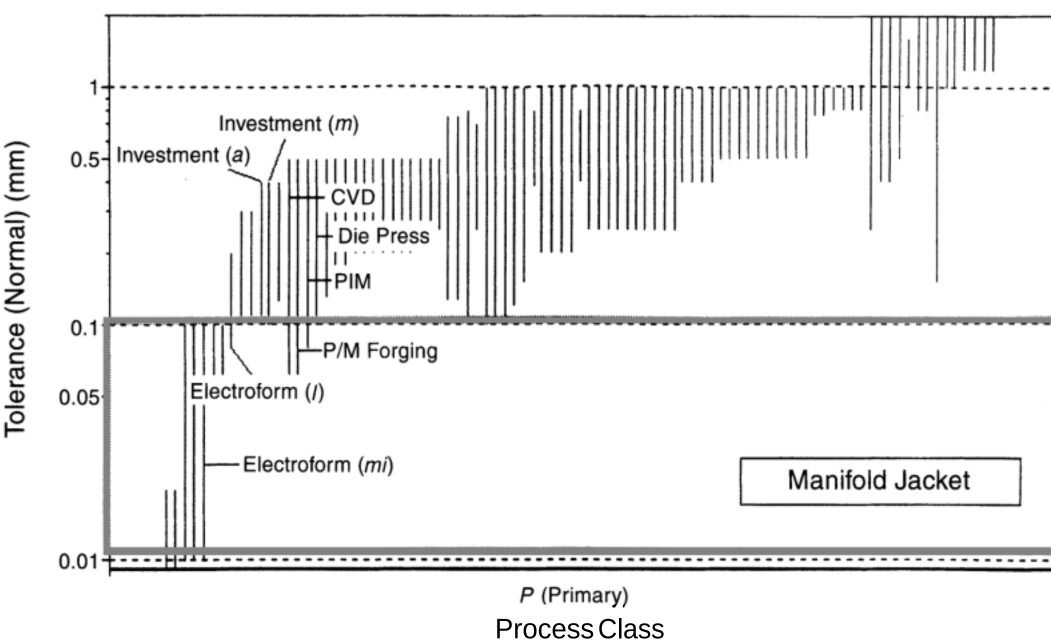

Fig. 12.11 A chart of tolerance against process class. The box isolates primary processes which are capable of tolerance levels of 0.1 mm or better.

The processes which passed all the selection stages so far are listed in Table 12.10. The final step is to rank them. Figure 12.12 shows the economic batch size for discrete processes (selected from the process-class menu), allowing this ranking. It indicates that, for a batch size of 10, automated investment casting is not economic, leaving two processes which are competitive: electro-forming and manual investment casting.

Conclusions and postscript

Electro-forming and *investment casting* emerged as the suitable candidates for making the manifold jacket. A search for further information in the sources listed in Chapter 11 reveals that electro-forming of nickel is established practice and that components as large as 20 kg are routinely made by this process. It looks like the best choice.

Related case studies

Case Study 12.8: Computer-based selection — a spark plug insulator

Table 12.10 Processes capable of making the manifold jacket

Process	*Comment*
Investment casting (manual)	Practical choice
Investment casting (automated)	Eliminated on economic grounds
Electro-forming	Practical choice

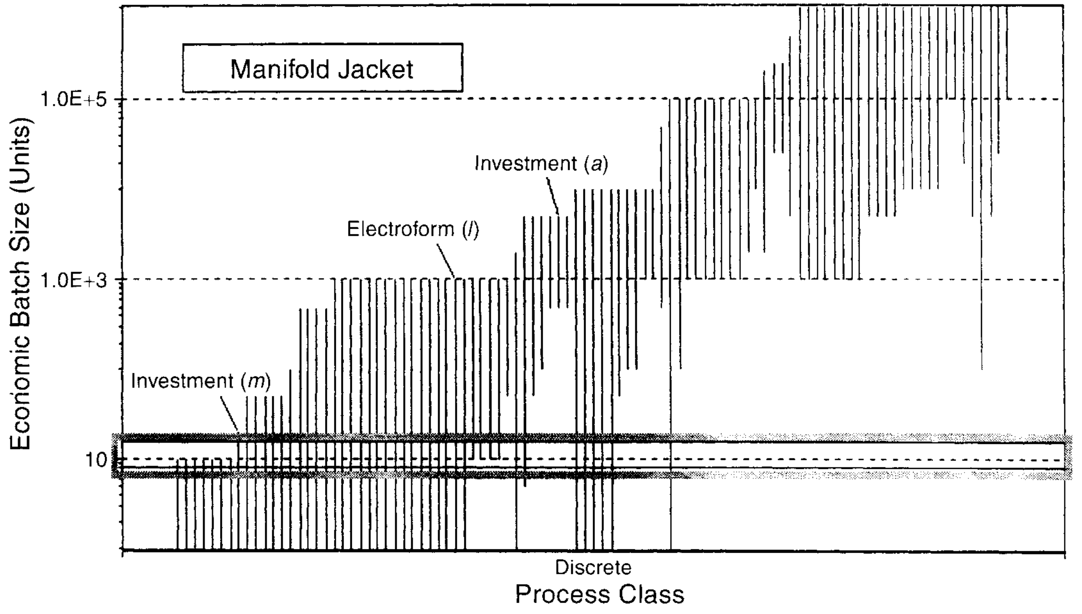

Fig. 12.12 A chart of economic batch size against process class. Three processes have passed all the stages. They are labelled.

12.8 Computer-based selection — a spark plug insulator

This is the second of two case studies illustrating the use of computer-based selection methods.

The design requirements

The anatomy of a spark plug is shown schematically in Figure 12.13. It is an assembly of components, one of which is the insulator. This is to be made of a ceramic, *alumina*, with the shape shown in the figure: an axisymmetric-hollow-stepped shape of low complexity. It weighs about 0.05 kg, has an average section thickness of 2.6 mm and a minimum section of 1.2 mm. Precision is important, since the insulator is part of an assembly; the design specifies a precision of ± 0.2 mm and a surface finish of better than 10 μm and, of course, cost should be as low as possible. Table 12.11 summarizes the requirements.

The selection

As in the previous case study, we set up four selection stages. The first (Figure 12.14) combines the requirements of material and mass. Here we have selected the subset of ceramic-shaping processes which can produce components with a mass range of 0.04 to 0.06 kg bracketing that of the insulator. The second stage (Figure 12.15) establishes that the process is a primary one and that it can cope

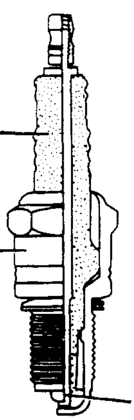

Fig. 12.13 A spark plug.

Table 12.11 Spark plug insulator: design requirements

Constraint	*Value*
Material class	Ceramic (alumina)
Process class	Primary, discrete
Shape class	Prismatic-axisymmetric-hollow-stepped
Weight ($\rho = 3000\,kg/m^3$)	0.05 kg
Min. section	1.2 mm
Mean precision	$< \pm 0.2$ mm
Roughness	<10 μm
Batch size	100 000

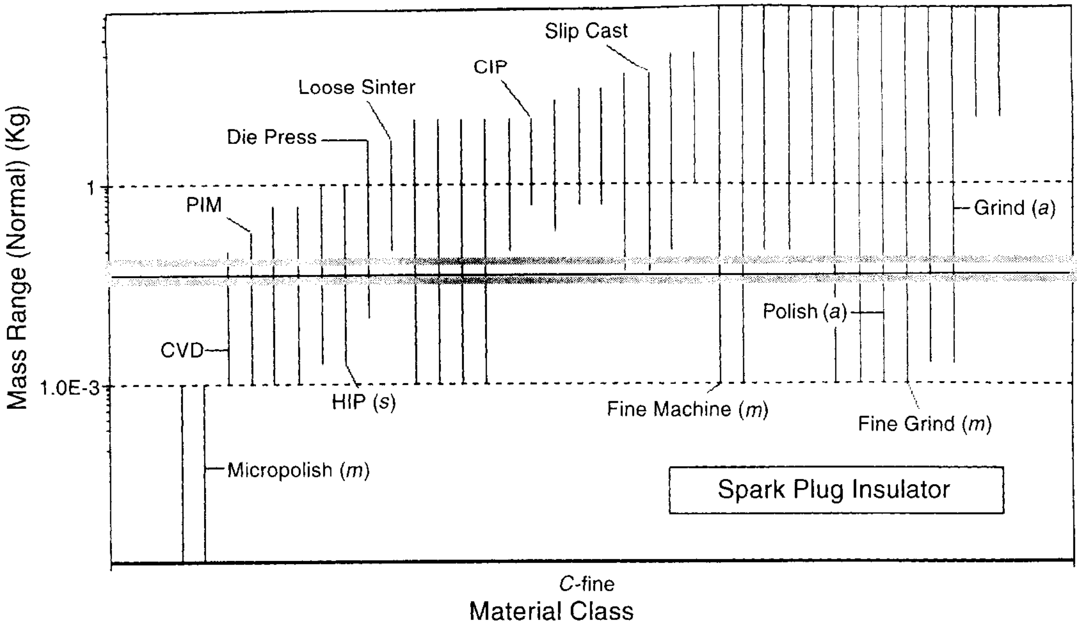

Fig. 12.14 A chart of mass range against material class. The box isolates processes which can shape fine ceramics to the desired mass range.

with the section thickness of the insulator (1 to 4 mm). The third stage (Figure 12.16) deals with shape and precision: processes capable of making 'prismatic-axisymmetric-hollow-stepped' shapes are plotted, and the selection box isolates the ones which can achieve tolerances better than ±0.2 mm.

The three stages allowed the identification of processes which are capable of meeting the design requirements for the insulator. They are listed in Table 12.12: die pressing of powder followed by sintering, powder injection moulding with sintering (PIM) and chemical vapour deposition onto a shaped pre-form (CVD). But this says nothing of the economics of manufacture. A final stage, shown in Figure 12.17, gives an approximate ranking, using the *economic batch size* as the ranking attribute. The first two processes are economic at a batch size of 100 000; the third is not.

Postscript

Insulators are made commercially by die pressing followed by sintering. According to our selection, PIM is a viable alternative and should be investigated further. More detailed cost analysis would be required before a final decision is made. Spark plugs have a very competitive market and, therefore, the cost of manufacturing should be kept low by choosing the cheapest route.

Table 12.12 Processes capable of making the spark plug insulator

Process	*Comment*
Die pressing and sintering	Practical choice
Powder injection moulding (PIM)	Practical choice
Chemical-vapour deposition (CVD)	Eliminated on economic grounds

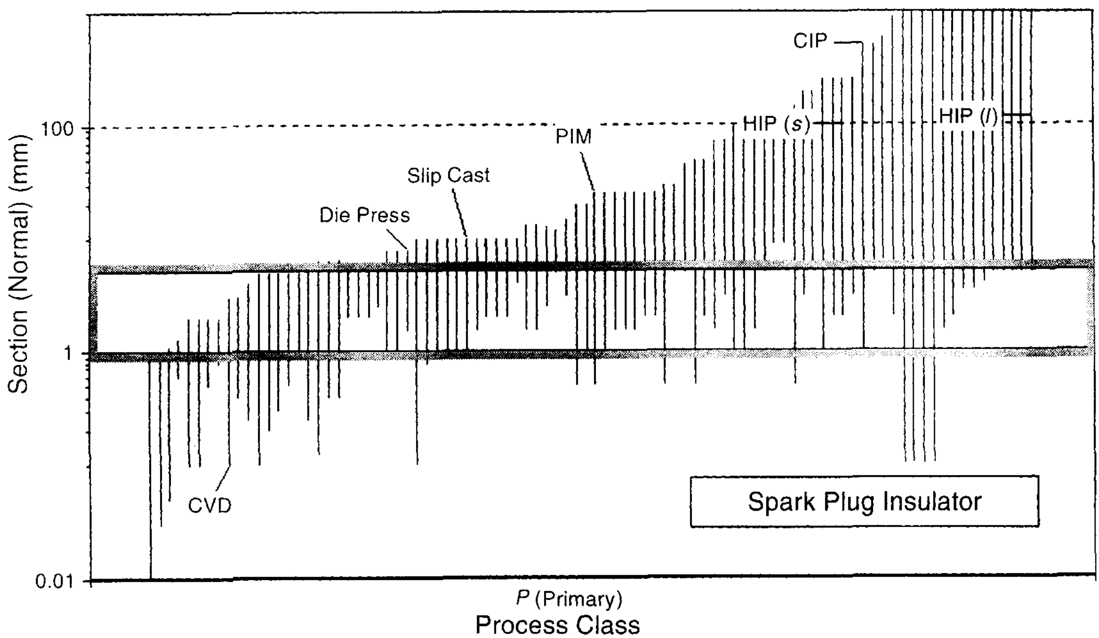

Fig. 12.15 A chart of section thickness range against process class. The chart identifies primary processes capable of making sections in the range 1–4 mm.

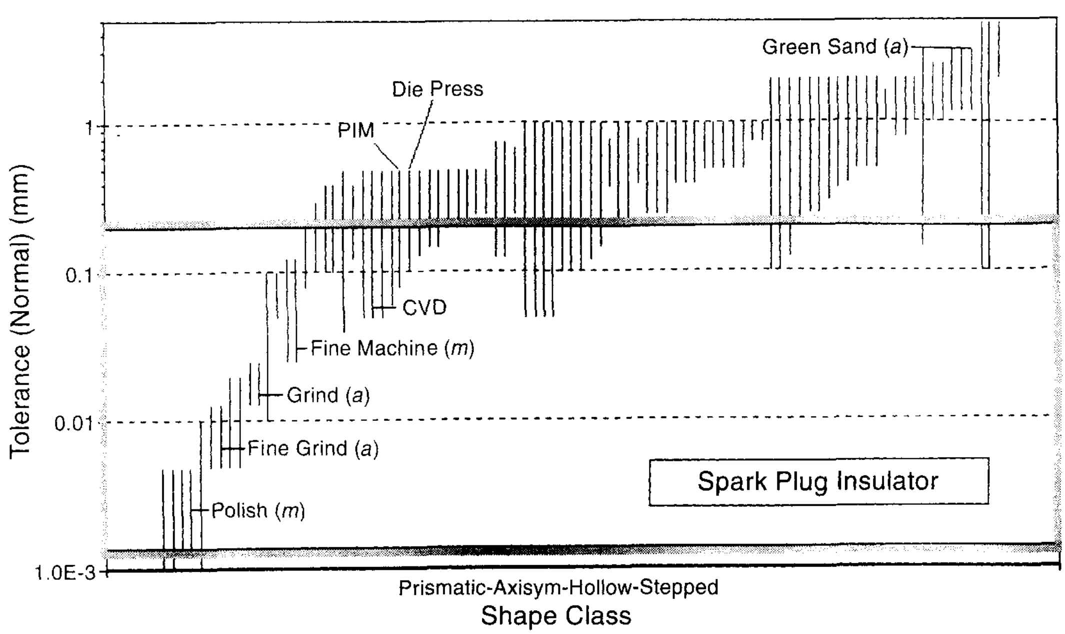

Fig. 12.16 A chart of tolerance against shape class. The chart identifies processes which can make prismatic-axisymmetric-hollow-stepped shapes with a tolerance of 0.2 mm or better.

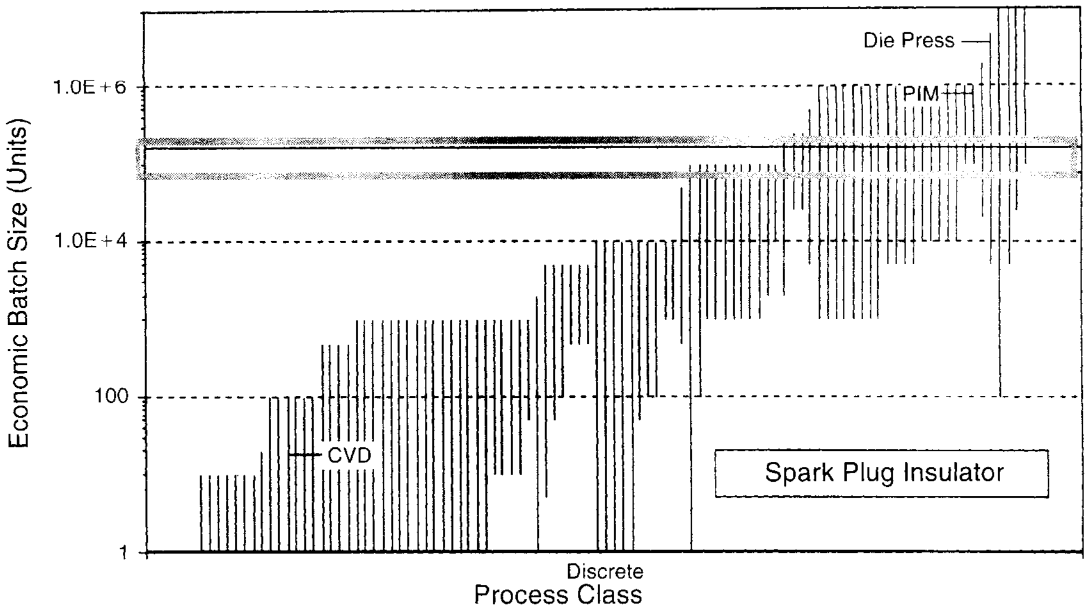

Fig. 12.17 A chart of economic batch size against process class. The three processes which passed the preceding selection stages are labelled. The box isolates the ones which are economic at a batch size of 100 000.

Related case studies

Case Study 12.7: Computer-based selection — a manifold jacket

12.9 Summary and conclusions

Process selection, at first sight, looks like a black art: the initiated know; the rest of the world cannot even guess how they do it. But this — as the chapter demonstrates — is not really so. The systematic approach, developed in Chapter 11 and illustrated here, identifies a subset of viable processes using design information only: size, shape, complexity, precision, roughness and material — itself chosen by the systematic method of Chapter 5. It does not identify the single, best, choice; that depends on too many case-specific considerations. But, by identifying candidates, it directs the user to data sources (starting with those listed in the Further reading of Chapters 11 and 13) which provide the details needed to make a final selection.

The case studies, deliberately, span an exceptional range of size, shape and material. In each, the systematic method leads to helpful conclusions.

12.10 Further reading

Atomic-force microscope design

Albrecht, T.R., Akamine, S., Carver, T.E. and Quate, C.F. (1990) 'Microfabrication of cantilever styli for the atomic force microscope', *J. Vac. Sci. Technol.*, **A8**(4), 3386.

Ceramic-forming methods

Richerson, D.W. (1982) *Modern Ceramic Engineering*, Marcel Dekker, New York.

Economics of manufacture

Kalpakjian, D. (1985) *Manufacturing Processes for Engineering Materials*, Addison Wesley, Reading, MA.

Computer-based process selection

CPS (Cambridge Process Selector) (1998), Granta Design, Trumpington Mews, 40B High Street, Trumpington, Cambridge CB2 2LS, UK.

Esawi, A. and Ashby, M.F. (1998) 'Computer-based selection of manufacturing processes', *J. Engineering Manufacture*.

Esawi, A. and Ashby, M.F. (1998) 'Computer-based selection of manufacturing processes, Part 1: methods and software; Part 2, case studies', Cambridge University Engineering Department Report TR 50, May 1997.