PART 1

QUANTITATIVE METHODS OF MATERIALS SELECTION

CHAPTER 1

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1 INTRODUCTION

It is estimated that there are more than 40,000 currently useful metallic alloys and probably close to that number of nonmetallic engineering materials such as plastics, ceramics and glasses, composite materials, and semiconductors. This large number of materials and the many manufacturing processes available to the engineer, coupled with the complex relationships between the different selection parameters, often make the selection of a materials for a given component a difficult task. If the selection process is carried out haphazardly, there will be the risk of overlooking a possible attractive alternative material. This risk can be reduced by adopting a systematic material selection procedure. A variety of quantitative selection procedures have been developed to analyze the large amount of data involved in the selection process so that a systematic evaluation

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can be made.[1–11] Several of the quantitative procedures can be adapted to use computers in selection from a data bank of materials.[12–15]

Experience has shown that it is desirable to adopt the holistic decision-making approach of concurrent engineering in product development in most industries. With concurrent engineering, materials and manufacturing processes are considered in the early stages of design and are more precisely defined as the design progresses from the concept to the embodiment and finally the detail stages. Figure 1 defines the different stages of design and shows the related activities of the material and manufacturing process selection. The figure illustrates the progressive nature of materials and process selection and defines three stages of selection—namely initial screening, developing and comparing alternatives, and selecting the optimum solution. Sections 2, 3, and 4 of this chapter discuss these three stages of material and process selection in more detail, and Section 5 gives a case study to illustrate the procedure.

Although the materials and process selection is often thought of in terms of new product development, there are many other incidents where materials substitution is considered for an existing product. Issues related to material substitution are discussed in Section 6 of this chapter.

Unlike the exact sciences, where there is normally only one single correct solution to a problem, materials selection and substitution decisions require the consideration of conflicting advantages and limitations, necessitating compromises and trade-offs; as a consequence, different satisfactory solutions are possible. This is illustrated by the fact that similar components performing similar functions, but produced by different manufacturers, are often made from different materials and even by different manufacturing processes.

2 INITIAL SCREENING OF MATERIALS

In the first stages of development of a new product, the following questions may be posed: What is it? What does it do? How does it do it? To answer these questions it is necessary to specify the performance requirements of the different parts involved in the design and to broadly outline the main materials performance and processing requirements. This allows the initial screening of materials whereby certain classes of materials and manufacturing processes may be eliminated and others chosen as likely candidates.

2.1 Analysis of Material Performance Requirements

The material performance requirements can be divided into five broad categories, namely functional requirements, processability requirements, cost, reliability, and resistance to service conditions.[1]

Functional Requirements

Functional requirements are directly related to the required characteristics of the part or the product. For example, if the part carries a uniaxial tensile load, the yield strength of a candidate material can be directly related to the load-carrying capacity of the product. However, some characteristics of the part or product may not have simple correspondence with measurable material properties, as in the case of thermal shock resistance, wear resistance, reliability, etc. Under these conditions, the evaluation process can be quite complex and may depend upon

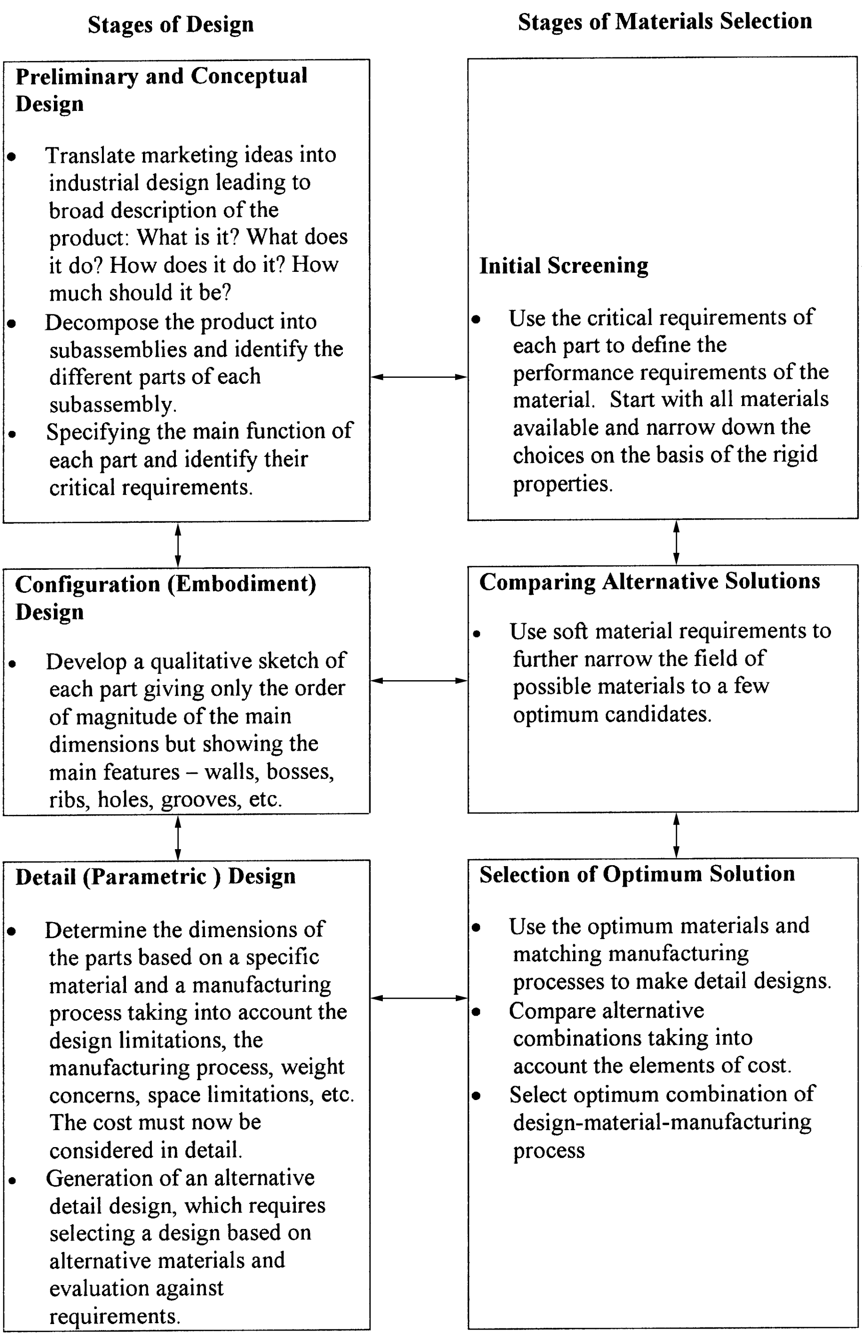

Fig. 1 Stages of design and the related stages of materials selection.

predictions based on simulated service tests or upon the most closely related mechanical, physical, or chemical properties. For example, thermal shock resistance can be related to thermal expansion coefficient, thermal conductivity, modulus of elasticity, ductility, and tensile strength. On the other hand, resistance to stress corrosion cracking can be related to tensile strength, K_{ISCC}, and electrochemical potential.

Processability Requirements

The processability of a material is a measure of its ability to be worked and shaped into a finished part. With reference to a specific manufacturing method, processability can be defined as castability, weldability, machinability, etc. Ductility and hardenability can be relevant to processability if the material is to be deformed or hardened by heat treatment, respectively. The closeness of the stock form to the required product form can be taken as a measure of processability in some cases.

It is important to remember that processing operations will almost always affect the material properties so that processability considerations are closely related to functional requirements.

Cost

Cost is usually an important factor in evaluating materials because in many applications there is a cost limit for a material intended to meet the application requirements. When the cost limit is exceeded, the design may have to be changed to allow for the use of a less expensive material. The cost of processing often exceeds the cost of the stock material. In some cases, a relatively more expensive material may eventually yield a less expensive product than a low-priced material that is more expensive to process.

Reliability Requirements

Reliability of a material can be defined as the probability that it will perform the intended function for the expected life without failure. Material reliability is difficult to measure because it is not only dependent upon the material's inherent properties, but it is also greatly affected by its production and processing history. Generally, new and nonstandard materials will tend to have lower reliability than established, standard materials.

Despite difficulties of evaluating reliability, it is often an important selection factor that must be taken into account. Failure analysis techniques are usually used to predict the different ways in which a product can fail and can be considered as a systematic approach to reliability evaluation. The causes of failure of a part in service can usually be traced back to defects in materials and processing, to faulty design, unexpected service conditions, or misuse of the product.

Resistance to Service Conditions

The environment in which the product or part will operate plays an important role in determining the material performance requirements. Corrosive environments, as well as high or low temperatures, can adversely affect the performance of most materials in service. Whenever more than one material is involved in an application, compatibility becomes a selection consideration. In a thermal environment, for example, the coefficients of thermal expansion of all the materials involved may have to be similar in order to avoid thermal stresses. In wet environments, materials that will be in electrical contact should be chosen carefully to avoid galvanic corrosion. In applications where relative movement exists between different parts, wear resistance of the materials involved should be considered. The design should provide access for lubrication, otherwise self-lubricating materials have to be used.

2.2 Quantitative Methods for Initial Screening

Having specified the performance requirements of the different parts, the required material properties can be established for each of them. These properties may be quantitative or qualitative, essential or desirable. For example, the function of a connecting rod in an internal combustion engine is to connect the piston to the crank shaft. The performance requirements are that it should transmit the power efficiently without failing during the expected life of the engine. The essential material properties are tensile and fatigue strengths, while the desirable properties that should be maximized are processability, weight, reliability, and resistance to service conditions. All these properties should be achieved at a reasonable cost. The selection process involves the search for the material or materials that would best meet those requirements. The starting point for materials selection is the entire range of engineering materials. At this stage, creativity is essential in order to open up channels in different directions and not to let traditional thinking interfere with the exploration of ideas. A steel may be the best material for one design concept while a plastic is best for a different concept, even though the two designs provide the same function.

After all the alternatives have been suggested, the ideas that are obviously unsuitable are eliminated and attention is concentrated on those that look practical. At the end of this phase, quantitative methods can be used for initial screening in order to narrow down the choices to a manageable number for subsequent detailed evaluation. Following are some of the quantitative methods for initial screening of materials.

Limits on Material Properties

Initial screening of materials can be achieved by first classifying their performance requirements into two main categories[1]:

- Rigid, or go–no-go, requirements
- Soft, or relative, requirements

Rigid requirements must be met by the material if it is to be considered at all. Such requirements can be used for the initial screening of materials to eliminate the unsuitable groups. For example, metallic materials are eliminated when selecting materials for an electrical insulator. If the insulator is to be flexible, the field is narrowed further as all ceramic materials are eliminated. Other examples of the material rigid requirements include behavior under operating temperature, resistance to corrosive environment, ductility, electrical and thermal conductivity or insulation, and transparency to light or other waves. Examples of process rigid requirements include batch size, production rate, product size and shape, tolerances, and surface finish. Whether or not the equipment or experience for a given manufacturing process exist in a plant can also be considered as a hard requirement in many cases. Compatibility between the manufacturing process and the material is also an important screening parameter. For example, cast irons are not compatible with sheet metal forming processes and steels are not easy to process by die casting. In some cases, eliminating a group of materials results in automatic elimination of some manufacturing processes. For example, if plastics are eliminated because service temperature is too high, injection and transfer molding should be eliminated as they are unsuitable for other materials.

Soft, or relative, requirements are subject to compromise and trade-offs. Examples of soft requirements include mechanical properties, specific gravity, and cost. Soft requirements can be compared in terms of their relative importance, which depends on the application under study.

Cost per Unit Property Method

The cost per unit property method is suitable for initial screening in applications where one property stands out as the most critical service requirement.[1] As an example, consider the case of a bar of a given length (L) to support a tensile force (F). The cross-sectional area (A) of the bar is given by

$$A = F/S \tag{1}$$

where S = working stress of the material, which is related to its yield strength by an appropriate factor of safety.

The cost of the bar (C') is given by

$$C' = C\rho AL = (C\rho FL)/S \tag{2}$$

where C = cost of the material per unit mass
ρ = density of the material

Since F and L are constant for all materials, comparison can be based on the cost of unit strength, which is the quantity:

$$[(C\rho)/S] \tag{3}$$

Materials with lower cost per unit strength are preferable. If an upper limit is set for the quantity $[(C\rho)/S]$, then materials satisfying this condition can be identified and used as possible candidates for more detailed analysis in the next stage of selection.

The working stress of the material in Eqs. 1, 2, and 3 is related to the static yield strength of the material since the applied load is static. If the applied load is alternating, it is more appropriate to use the fatigue strength of the material. Similarly, the creep strength should be used under loading conditions that cause creep.

Equations similar to 2 and 3 can be used to compare materials on the basis of cost per unit stiffness when the important design criterion is deflection in the bar. In such cases, S is replaced by the elastic modulus of the material. The

Table 1 Formulas for Estimating Cost per Unit Property[1]

Cross Section and Loading Condition	Cost per Unit Strength	Cost per Unit Stiffness
Solid cylinder in tension or compression	$C\rho/S$	$C\rho/E$
Solid cylinder in bending	$C\rho/S^{2/3}$	$C\rho/E^{1/2}$
Solid cylinder in torsion	$C\rho/S^{2/3}$	$C\rho/G^{1/2}$
Solid cylindrical bar as slender column	—	$C\rho/E^{1/2}$
Solid rectangle in bending	$C\rho/S^{1/2}$	$C\rho/E^{1/3}$
Thin-walled cylindrical pressure vessel	$C\rho/S$	—

above equations can also be modified to allow comparison of different materials under loading systems other than uniaxial tension. Table 1 gives some formulas for the cost per unit property under different loading conditions based on either yield strength or stiffness.

Ashby's Method

Ashby's material selection charts[4,5,9,10] are also useful for initial screening of materials. Figure 2 plots the strength against density for a variety of materials. Depending upon the geometry and type of loading, different S–ρ relationships apply as shown in Table 1. For simple axial loading, the relationship is S/ρ. For solid rectangle under bending, $S^{1/2}/\rho$ applies, and for solid cylinder under bending or torsion the relationship $S^{2/3}/\rho$ applies. Lines with these slopes are shown in Fig. 2. Thus if a line is drawn parallel to the line $S/\rho = C$, all the materials that lie on the line will perform equally well under simple axial loading conditions. Materials above the line are better and those below it are worse. A similar diagram can be drawn for elastic modulus against density and formulas similar to those in Table 1 can be used to screen materials under conditions where stiffness is a major requirement

Dargie's Method

The initial screening of materials and processes can be a tedious task if performed manually from handbooks and supplier catalogs. This difficulty has prompted the introduction of several computer-based systems for materials and/or process selection.[12–15] As an illustrative example, the system (MAPS 1) proposed by Dargie et al.[15] will be briefly described here. For this system, Dargie et al. proposed a part classification code similar to that used in group technology.

The first five digits of the MAPS 1 code are related to the elimination of unsuitable manufacturing processes. The first digit is related to the batch size. The second digit characterizes the bulk and depends on the major dimension and whether the part is long, flat, or compact. The third digit characterizes the shape, which is classified on the basis of being prismatic, axisymmetric, cup shaped, nonaxisymmetric, and nonprismatic. The fourth digit is related to tolerance and the fifth digit is related to surface roughness

The next three digits of the MAPS 1 code are related to the elimination of unsuitable materials. The sixth digit is related to service temperature. The seventh digit is related to the acceptable corrosion rate. The eighth digit characterizes the type of environment to which the part is exposed.

The system uses two types of databases for preliminary selection:

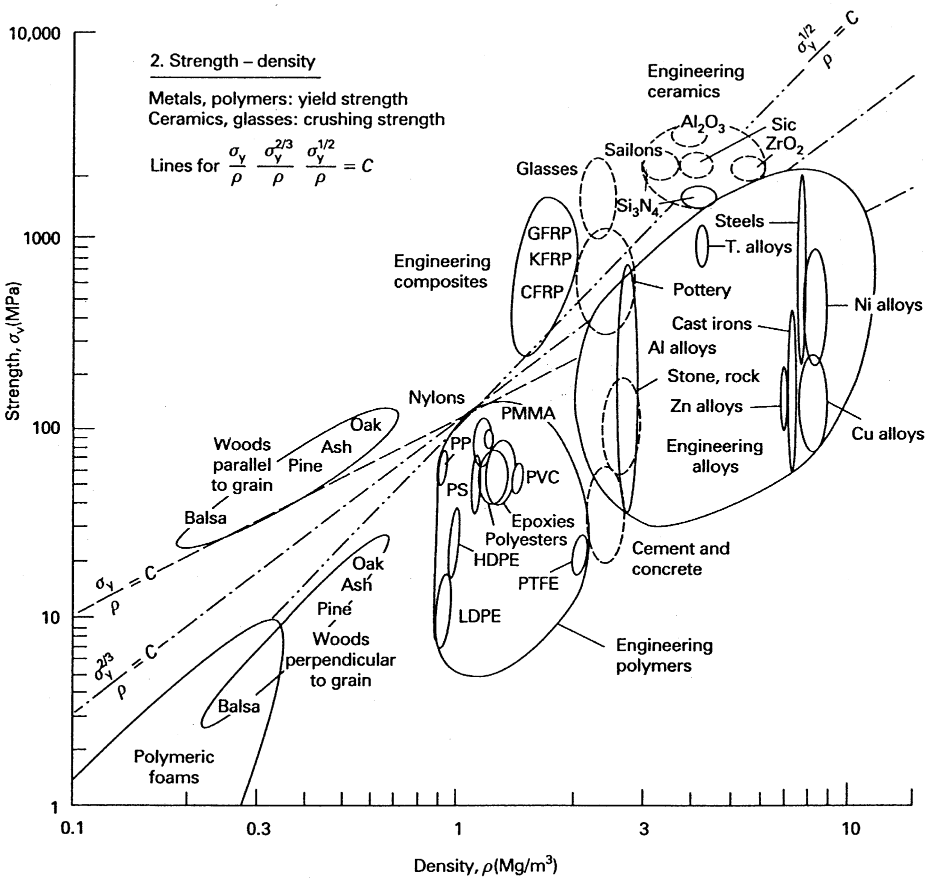

Fig. 2 Example of Ashby's materials selection charts (from Ref. 10, with permission from The Institute of Materials).

- Suitability matrices
- Compatibility matrix

The suitability matrices deal with the suitability of processes and materials for the part under consideration. Each of the code digits has a matrix. The columns of the matrix correspond to the value of the digit and the rows correspond to the processes and materials in the database. The elements of the matrix are either 0, indicating unsuitability, or 2 indicating suitability.

The compatibility matrix expresses the compatibility of the different combinations of processes and materials. The columns of the matrix correspond to the materials while the rows correspond to the processes. The elements of the matrix are either 0 for incompatible combinations, 1 for difficult or unusual combinations, or 2 for combinations used in usual practice.

Based on the part code, the program generates a list of candidate combinations of materials and processes to produce it. This list helps the designer to identify possible alternatives early in the design process and to design for ease of manufacture.

3 COMPARING ALTERNATIVE SOLUTIONS

After narrowing down the field of possible materials using one or more of the quantitative initial screening methods described in Section 2, quantitative methods can be used to further narrow the field of possible materials and matching manufacturing processes to a few optimum candidates that have good combinations of soft requirements. Several such methods are described in Refs. 1 and 2 and following is a description of one of the methods.

3.1 Weighted-Properties Method

In the weighted-properties method each material requirement, or property, is assigned a certain weight, depending on its importance to the performance of the part in service.[1] A weighted-property value is obtained by multiplying the numerical value of the property by the weighting factor (α). The individual weighted-property values of each material are then summed to give a comparative materials performance index (γ). Materials with the higher performance index (γ) are considered more suitable for the application.

Digital Logic Method

In the cases where numerous material properties are specified and the relative importance of each property is not clear, determinations of the weighting factors, α, can be largely intuitive, which reduces the reliability of selection. The digital logic approach can be used as a systematic tool to determine α.[1] In this procedure evaluations are arranged such that only two properties are considered at a time. Every possible combination of properties or goals is compared and no shades of choice are required, only a yes or no decision for each evaluation. To determine the relative importance of each property or goal a table is constructed, the properties or goals are listed in the left-hand column, and comparisons are made in the columns to the right, as shown in Table 2.

In comparing two properties or goals, the more important goal is given numerical one (1) and the less important is given zero (0). The total number of possible decisions $N = n\ (n - 1)/2$, where n is the number of properties or goals under consideration. A relative emphasis coefficient or weighting factor,

Table 2 Determination of Relative Importance of Goals Using Digital Logic Method[1]

	Number of Positive Decisions $N = n(n - 1)/2$											
Goals	1	2	3	4	5	6	7	8	9	10	Positive Decisions	Relative Emphasis Coefficient α
1	1	1	0	1							3	0.3
2	0				1	0	1				2	0.2
3		0			0			1	0		1	0.1
4			1			1		0		0	2	0.2
5				0			0		1	1	2	0.2
	Total number of positive decisions										10	$\Sigma\alpha = 1.0$

α, for each goal is obtained by dividing the number of positive decisions for each goal (m) into the total number of possible decisions (N). In this case $\Sigma\alpha = 1$.

To increase the accuracy of decisions based on the digital logic approach, the yes–no evaluations can be modified by allocating gradation marks ranging from 0 (no difference in importance) to 3 (large difference in importance). In this case, the total gradation marks for each selection criterion are reached by adding up the individual gradation marks. The weighting factors are then found by dividing these total gradation marks by their grand total.

Performance Index

In its simple form, the weighted-properties method has the drawback of having to combine unlike units, which could yield irrational results. This is particularly true when different mechanical, physical, and chemical properties with widely different numerical values are combined. The property with higher numerical value will have more influence than is warranted by its weighting factor. This drawback is overcome by introducing scaling factors. Each property is so scaled that its highest numerical value does not exceed 100. When evaluating a list of candidate materials, one property is considered at a time. The best value in the list is rated as 100 and the others are scaled proportionally. Introducing a scaling factor facilitates the conversion of normal material property values to scaled dimensionless values. For a given property, the scaled value, B, for a given candidate material is equal to:

$$B = \text{Scaled property} = \frac{\text{Numerical value of prperty} \times 100}{\text{Maximum value in the list}} \tag{4}$$

For properties such as cost, corrosion or wear loss, weight gain in oxidation, etc., a lower value is more desirable. In such cases, the lowest value is rated as 100 and B is calculated as:

$$B = \text{Scaled property} = \frac{\text{Minimum value in the list} \times 100}{\text{Numerical value of property}} \tag{5}$$

For material properties that can be represented by numerical values, application of the above procedure is simple. However, with properties such as corrosion and wear resistance, machinability and weldability, etc., numerical values are rarely given and materials are usually rated as very good, good, fair, poor, etc. In such cases, the rating can be converted to numerical values using an arbitrary scale. For example, corrosion resistance rating—excellent, very good, good, fair, and poor—can be given numerical values of 5, 4, 3, 2, and 1, respectively. After scaling the different properties, the material performance index (γ) can be calculated as:

$$\text{Material performance index} = \gamma = \sum_{i=1}^{n} B_i\alpha_i \tag{6}$$

where i is summed over all the n relevant properties.

Cost (stock material, processing, finishing, etc.) can be considered as one of the properties and given the appropriate weighting factor. However, if there is a large number of properties to consider, the importance of cost may be emphasized by considering it separately as a modifier to the material performance index (γ). In the cases where the material is used for space filling, cost can be introduced on per unit volume basis. A figure of merit (M) for the material can then be defined as:

$$M = \gamma/(C\rho) \tag{7}$$

where C = total cost of the material per unit weight (stock, processing, finishing, etc.)
ρ = density of the material.

When an important function of the material is to bear stresses, it may be more appropriate to use the cost of unit strength instead of the cost per unit volume. This is because higher strength will allow less material to be used to bear the load, and the cost of unit strength may be a better representative of the amount of material actually used in making the part. In this case, Eq. 7 is rewritten as:

$$M = \gamma/C' \tag{8}$$

where C' is determined from Table 1 depending on the type of loading.

This argument may also hold in other cases where the material performs an important function such as electrical conductivity or thermal insulation. In these cases the amount of the material, and consequently the cost, are directly affected by the value of the property.

When a large number of materials with a large number of specified properties are being evaluated for selection, the weighted-properties method can involve a large number of tedious and time-consuming calculations. In such cases, the use of a computer would facilitate the selection process. The steps involved in the weighted-properties method can be written in the form of a simple computer program to select materials from a data bank. An interactive program can also include the digital logic method to help in determining the weighting factors.

4 SELECTING THE OPTIMUM SOLUTION

Candidates that have the most promising performance indices can each now be used to develop a detail design. Each detail design will exploit the points of strength of the material, avoid the weak points, and reflect the requirements of the manufacturing processes needed for the material. The different designs are then compared, taking the cost elements into consideration, in order to arrive at the optimum design–material–process combination.[16]

5 CASE STUDY IN MATERIAL SELECTION

The following case study illustrates the procedure for materials selection as described in Sections 2, 3, and 4 and is based on Ref. 16. The objective is to select the least expensive component that satisfies the requirements for a simple structural component for a sailing-boat mast in the form of a hollow cylinder of length 1000 mm, which is subjected to compressive axial forces of 153 kN. Because of space and weight limitations, the outer diameter of the component should not exceed 100 mm, the inner diameter should not be less than 84 mm, and the mass should not exceed 3 kg. The component will be subjected to mechanical impact and spray of water. Assembly to other components requires the presence of relatively small holes.

5.1 Material Performance Requirements

Possible modes of failure and the corresponding material properties that are needed to resist failure for the present component include:

- Catastrophic fracture due to impact loading, especially near assembly holes, is resisted by high fracture toughness of the material. This is a rigid material requirement and will be used for initial screening of materials.
- Plastic yielding is resisted by high yield strength. This is a soft material requirement, but a lower limit will be determined by the limitation on the outer diameter.
- Local and global buckling are resisted by high elastic modulus. This is a soft material requirement, but a lower limit will be determined by the limitation on the outer diameter.
- Internal fiber buckling for fiber-reinforced materials is resisted by high modulus of elasticity of the matrix and high volume fraction of fibers in the loading direction. This is a soft material requirement, but a lower limit will be determined by the limitation on the outer diameter.
- Corrosion, which can be resisted either by selecting materials with inherently good corrosion resistance or by protective coating.
- Reliability of the component in service. A factor of safety of 1.5 is taken for the axial loading, i.e., the working axial force will be taken as 230 kN in order to improve reliability.

In addition to the above requirements the limitations set on dimensions and weight should be observed.

5.2 Initial Screening of Materials

The requirement for fracture toughness of the material is used to eliminate ceramic materials. Because of the limitations set on the outer and inner diameters, the maximum possible cross section of the component is about 2300 mm^2. To avoid yielding under the axial working load, the yield strength of the material should be more than 100 MPa, which excludes engineering polymers, woods, and some of the lower strength engineering alloys; see Fig. 2. Corrosion resistance is desirable but will not be considered a factor for screening since the possibility of protection for less corrosion materials exists but will be considered as a soft requirement.

5.3 Comparing Alternative Solutions

Table 3 shows a sample of materials that satisfy the conditions set in the initial screening stage. In a real-life situation the list in the table could be much longer,

Table 3 Properties of Sample Candidate Materials[16]

Material	Yield Strength (MPa)	Elastic Modulus (GPa)	Specific Gravity	Corrosion Resistance[a]	Cost Category[b]
AISI 1020 (UNS G10200)	280	210	7.8	1	5
AISI 1040 (UNS G10400)	400	210	7.8	1	5
ASTM A242 type 1 (UNS K11510)	330	212	7.8	1	5
AISI 4130 (UNS G41300)	1520	212	7.8	4	3
AISI 316 (UNS S31600)	205	200	7.98	4	3
AISI 416 heat treated (UNS S41600)	440	216	7.7	4	3
AISI 431 heat treated (UNS S43100)	550	216	7.7	4	3
AA 6061 T6 (UNS A96061)	275	69.7	2.7	3	4
AA 2024 T6 (UNS A92024)	393	72.4	2.77	3	4
AA 2014 T6 (UNS A92014)	415	72.1	2.8	3	4
AA 7075 T6 (UNS A97075)	505	72.4	2.8	3	4
Ti–6Al–4V	939	124	4.5	5	1
Epoxy–70% glass fabric	1270	28	2.1	4	2
Epoxy–63% carbon fabric	670	107	1.61	4	1
Epoxy–62% aramid fabric	880	38	1.38	4	1

[a] 5 Excellent, 4 Very good, 3 Good, 2 Fair, 1 Poor.

[b] 5 Very inexpensive, 4 Inexpensive, 3 Moderate price, 2 Expensive, 1 Very expensive.

but the intent here is to illustrate the procedure. The yield strength, elastic modulus, specific gravity, corrosion resistance, and cost category are given for each of the materials. At this stage, it is sufficient to classify materials into very inexpensive, inexpensive, etc. Better estimates of the material and manufacturing cost will be needed in making the final decision in selection. Because the weight of the component is important in this application, specific strength and specific modulus would be better indicators of the suitability of the material (Table 4). The relative importance of the material properties is given in Table 5, and the performance indices of the different materials, as determined by the weighted-properties method, are given in Table 6. The seven candidate materials with high-performance indices ($\gamma > 45$) are selected for making actual component designs.

5.4 Selecting the Optimum Solution

As shown earlier, the possible modes of failure of a hollow cylinder include yielding, local and global buckling, and internal fiber buckling. These four failure modes are used to develop the design formulas for the mast component. For

Table 4 Properties of Sample Candidate Materials[16]

Material	Specific Strength (MPa)	Specific Modulus (GPa)	Corrosion Resistance[a]	Cost Category[b]
AISI 1020 (UNS G10200)	35.9	26.9	1	5
AISI 1040 (UNS G10400)	51.3	26.9	1	5
ASTM A242 type 1 (UNS K11510)	42.3	27.2	1	5
AISI 4130 (UNS G41300)	194.9	27.2	4	3
AISI 316 (UNS S31600)	25.6	25.1	4	3
AISI 416 heat treated (UNS S41600)	57.1	28.1	4	3
AISI 431 heat treated (UNS S43100)	71.4	28.1	4	3
AA 6061 T6 (UNS A96061)	101.9	25.8	3	4
AA 2024 T6 (UNS A92024)	141.9	26.1	3	4
AA 2014 T6 (UNS A92014)	148.2	25.8	3	4
AA 7075 T6 (UNS A97075)	180.4	25.9	3	4
Ti–6Al–4V	208.7	27.6	5	1
Epoxy–70% glass fabric	604.8	28	4	2
Epoxy–63% carbon fabric	416.2	66.5	4	1
Epoxy–62% aramid fabric	637.7	27.5	4	1

[a] 5 Excellent, 4 Very good, 3 Good, 2 Fair, 1 Poor.

[b] 5 Very inexpensive, 4 Inexpensive, 3 Moderate price, 2 Expensive, 1 Very expensive.

more details on the design and optimization procedure or Eqs. 9–12, please refer to Ref. 16.

$$\text{Condition for yielding: } F/A < \sigma_y \tag{9}$$

where σ_y = yield strength of the material
F = external working axial force
A = cross sectional area

$$\text{Condition for local buckling: } F/A < 0.121ES/D \tag{10}$$

Table 5 Weighting Factors

Property	Specific Strength (MPa)	Specific Modulus (GPa)	Corrosion Resistance	Relative Cost
Weighting factor (α)	0.3	0.3	0.15	0.25

Table 6 Calculation of the Performance Index

Material	Scaled Specific Strength * 0.3	Scaled Specific Modulus * 0.3	Scaled Corrosion Resistance * 0.15	Scaled Relative Cost * 0.25	Performance Index (γ)
AISI 1020 (UNS G10200)	1.7	12.3	3	25	42
AISI 1040 (UNS G10400)	2.4	12.3	3	25	42.7
ASTM A242 type 1 (UNS K11510)	2	12.3	3	25	42.3
AISI 4130 (UNS G41300)	9.2	12.3	6	15	42.5
AISI 316 (UNS S31600)	1.2	11.3	12	15	39.5
AISI 416 heat treated (UNS S41600)	2.7	12.7	12	15	42.4
AISI 431 heat treated (UNS S43100)	3.4	12.7	12	15	43.1
AA 6061 T6 (UNS A96061)	4.8	11.6	9	20	45.4
AA 2024 T6 (UNS A92024)	6.7	11.8	9	20	47.5
AA 2014 T6 (UNS A92014)	7	11.6	9	20	47.6
AA 7075 T6 (UNS A97075)	8.5	11.7	9	20	49.2
Ti–6Al–4V	9.8	12.5	15	5	42.3
Epoxy–70% glass fabric	28.4	12.6	12	10	63
Epoxy–63% carbon fabric	19.6	30	12	5	66.6
Epoxy–62% aramid fabric	30	12.4	12	5	59.4

where D = outer diameter of the cylinder
S = wall thickness of the cylinder
E = elastic modulus of the material

Condition for global buckling:

$$\sigma_y > F/A[1 + (LDA/1000I)\sec\{(F/EI)^{1/2}L/2\}] \qquad (11)$$

where I = second moment of area
L = length of the component

Condition for internal fiber buckling:

$$F/A < [E_m/4(1 + \nu_m)(1 - V_f^{1/2})] \qquad (12)$$

where E_m = elastic modulus of the matrix material
ν_m = Poisson's ratio of the matrix material
V_f = volume fraction of the fibers parallel to the loading direction

Figure 3 shows the optimum design range of component diameter and wall

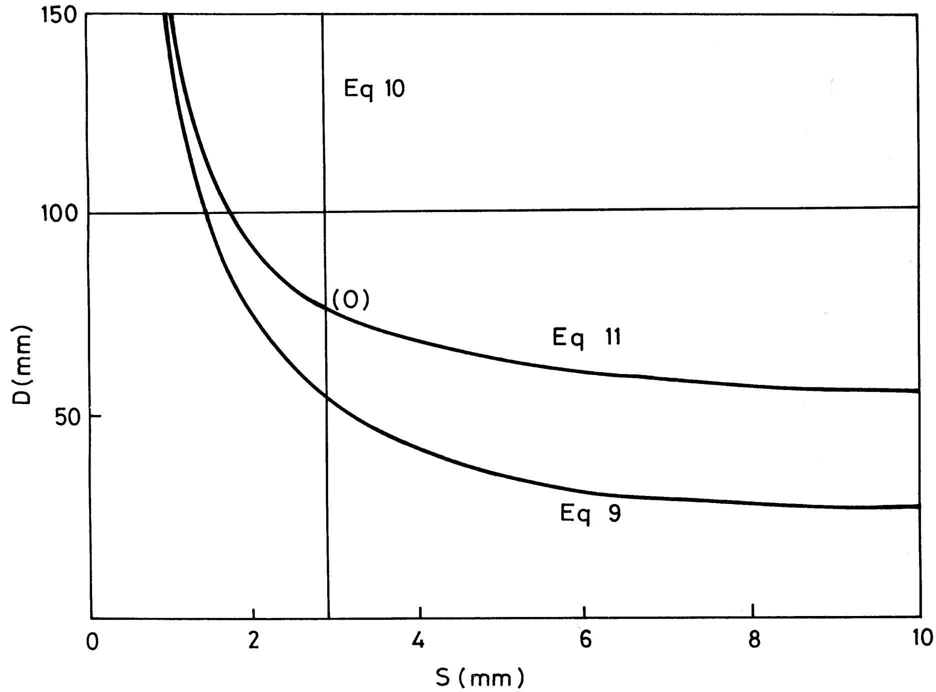

Fig. 3 Design range as predicted by Eqs. 9–11 for AA 7075 aluminum alloy. (Reprinted from *Materials and Design,* **13**, M. M. Farag and E. El-Magd, An Integrated Approach to Product Design, Materials Selection, and Cost Estimation, 323–327, © 1992, with permission from Elsevier Science.)

thickness as predicted by Eqs. 9–11 for AA 7075 aluminum alloy. Point (*O*) represents the optimum design. Similar figures were developed for the different candidate materials to determine the mast component's optimum design dimensions when made of the materials and the results as shown in Table 7. Although all the materials in Table 7 can be used to make safe components that comply

Table 7 Designs Using Candidate Materials with Highest Performance Indices[16]

Material	D_a (mm)	S (mm)	A (mm^2)	Mass (kg)	Cost/kg ($)	Cost of Component ($)
AA 6061 T6 (UNS A96061)	100	3.4	1065.7	2.88	8	23.2
AA 2024 T6 (UNS A92024)	88.3	2.89	801.1	2.22	8.3	18.4
AA 2014 T6 (UNS A92014)	85.6	2.89	776.6	2.17	9	19.6
AA 7075 T6 (UNS A97075)	78.1	2.89	709.1	1.99	10.1	20
Epoxy–70% glass fabric	78	4.64	1136.3	2.39	30.8	73.6
Epoxy–63% carbon fabric	73.4	2.37	546.1	0.88	99	87.1
Epoxy–62% aramid fabric	75.1	3.99	941.6	1.30	88	114.4

with the space and weight limitations, AA 2024 T6 is selected since it gives the least expensive solution.

6 MATERIALS SUBSTITUTION

The common reasons for materials substitution include:

- Taking advantage of new materials or processes
- Improving service performance, including longer life and higher reliability
- Meeting new legal requirements
- Accounting for changed operating conditions
- Reducing cost and making the product more competitive

Generally, a simple substitution of one material for another does not produce an optimum solution. This is because it is not possible to realize the full potential of a new material unless the component is redesigned to exploit its strong points and manufacturing characteristics. Following is a brief description of some of the quantitative methods that are available for making decisions in materials substitution.

6.1 Pugh Method

The Pugh method[17] is useful as an initial screening method in the early stages of design. In this method, a decision matrix is constructed as shown in Table 8. Each of the properties of a possible alternative new material is compared with the corresponding property of the currently used material and the result is recorded in the decision matrix as (+) if more favorable, (−) if less favorable, and (0) if the same. The decision on whether a new material is better than the currently used material is based on the analysis of the result of comparison, i.e., the total number of (+), (−), and (0). New materials with more favorable properties than drawbacks are selected as serious candidates for substitution and are used to redesign the component and for detailed analysis.

Table 8 Example of Use of Pugh Decision Matrix for Materials Substitution

Property	Currently Used Material	New Material (1)	New Material (2)	New Material (3)
Property 1	C1	−	+	+
Property 2	C2	+	+	+
Property 3	C3	+	+	−
Property 4	C4	0	+	−
Property 5	C5	−	0	−
Property 6	C6	0	0	0
Property 7	C7	−	−	0
Property 8	C8	−	+	0
Property 9	C9	−	0	0
Total (+)		2	5	2
Total (−)		5	1	3
Total (0)		2	3	4

6.2 Cost–Benefit Analysis

The cost–benefit analysis is more suitable for the detailed analysis involved in making the final material substitution decision.[1] Because new materials are usually more complex and often require closer control and even new technologies for their processing, components made from such materials are more expensive. This means that for materials substitution to be economically feasible, the economic gain as a result of improved performance ΔB should be more than the additional cost incurred as a result of substitution ΔC.

$$\Delta B - \Delta C > 1 \tag{13}$$

For this analysis it is convenient to divide the cost of materials substitution ΔC into:

- *Cost Differences in Direct Material and Labor.* New materials often have better performance but are more expensive. When smaller amounts of the new material are used to make the product, the increase in direct material cost may not be as great as it would appear at first. Cost of labor may not be an important factor in substitution if the new materials do not require new processing techniques and assembly procedures. If, however, new processes are needed, new cycle times may result and the difference in productivity has to be carefully assessed.
- *Cost of Redesign and Testing.* Using new materials usually involves design changes and testing of components to ensure that their performance meets the requirements. The cost of redesign and testing can be considerable in the case of critical components.
- *Cost of New Tools and Equipment.* Changing materials can have considerable effect on life and cost of tools, and it may influence the heat treatment and finishing processes. This can be a source of cost saving if the new material does not require the same complex treatment or finishing processes used for the original material. The cost of equipment needed to process new materials can be considerable if the new materials require new production facilities as in the case of replacing metals with plastics.

Based on the above analysis, the total cost (ΔC) of substituting a new material, n, in place of an original material, o, in a given part is:

$$\Delta C = (P_n M_n - P_o M_o) + f(C_t/N) + (T_n - T_o) + (L_n - L_o) \tag{14}$$

where P_n, P_o = price/unit mass of new and original materials used in the part
M_n, M_o = mass of new and original materials used in the part
f = capital recovery factor; it can be taken as 15% in the absence of information
C_t = cost of transition from original to new materials
N = total number of new parts produced
T_n, T_o = tooling cost per part for new and original materials
L_n, L_o = labor cost per part using new and old materials

The gains as a result of improved performance ΔB can be estimated based on the expected improved performance of the component, which can be related to the increase in performance index of the new material compared with the currently used material. Such increases include the saving gained as a result of weight reduction or increased service life of the component.

$$\Delta B = A(\gamma_n - \gamma_o) \tag{15}$$

where γ_n, γ_o = performance indices of the new and original materials, respectively

A = benefit of improved performance of the component expressed in dollars per unit increase in material performance index γ.

7 CASE STUDY IN MATERIALS SUBSTITUTION

In the case study in materials selection that was discussed in Section 5, the aluminum alloy AA 2024 T6 was selected since it gives the least expensive solution. Of the seven materials in Table 7, AA 6061 T6, epoxy–70% glass fabric, and epoxy–62% aramid fabric result in components that are heavier and more expensive than those of the other four materials and will be rejected as they offer no advantage. Of the remaining four materials, AA 2024 T6 results in the least expensive but the heaviest component. The other three materials—AA 2014 T6, AA 7075 T6, and epoxy–63% carbon fabric—result in progressively lighter components at progressively higher cost.

For the cases where it is advantageous to have a lighter component, the cost–benefit analysis can be used in finding a suitable substitute for AA 2024 T6 alloy. For this purpose Eq. 15 is used with the performance index γ being considered as the weight of the component and ΔC being the difference in cost of component and A is the benefit expressed in dollars, of reducing the mass by 1 kg. Comparing the materials in pairs shows that:

For $A <$ \$7/kg saved, AA 2024 T6 is the optimum material.
For $A =$ \$7 − \$60.5/kg saved, AA 7075 T6 is a better substitute.
For $A >$ \$60.5/kg saved, Epoxy–63% carbon fabric is optimum.

8 SOURCES OF INFORMATION AND COMPUTER-ASSISTED SELECTION

One essential requisite to successful materials selection is a source of reliable and consistent data on materials properties. There are many sources of information, which include governmental agencies, trade associations, engineering societies, textbooks, research institutes, and materials producers. The ASM International has recently published a directory of materials property databases[18] that contains more than 500 data sources, including both specific databases and data centers. For each source, the directory gives a brief description of the available information, address, telephone number, e-mail, web site, and approximate cost if applicable. The directory also has indices by material and by property to help the user in locating the most appropriate source of material information. Much of the information is available on CD-ROM or PC disk, which makes it possible to integrate the data source in computer-assisted selection systems.

Other useful reviews of the sources of materials property data and information are also given in Refs. 19 and 20.

8.1 Computerized Materials Databases

Computerized materials databases are an important part of any computer-aided system for selection. With an interactive database, as in the case of *ASM Metal Selector,*[21] the user can define and redefine the selection criteria to gradually sift the materials and isolate the candidates that meet the requirements. In many cases, sifting can be carried out according to different criteria such as:

1. Specified numeric values of a set of material properties
2. Specified level of processability such as machinability, weldability, formability, availability, processing cost, etc.
3. Class of material, e.g., fatigue resistant, corrosion resistant, heat resistant, electrical materials, etc.
4. Forms such as rod, wire, sheet, tube, cast, forged, welded, etc.
5. Designations: Unified Numbering System (UNS) numbers, American Iron and Steel Institute (AISI) numbers, common names, material group or country of origin
6. Specifications, which allows the operator to select the materials that are acceptable to organizations such as the American Society for Testing and Materials (ASTM) and the Society of Automotive Engineers (SAE)
7. Composition, which allows the operator to select the materials that have certain minimum and/or maximum values of alloying elements

More than one of the above sifting criteria can be used to identify suitable materials. Sifting can be performed in the AND or OR modes. The AND mode narrows the search since the material has to conform to all the specified criteria. The OR mode broadens the search since materials that satisfy any of the requirements are selected.

The number of materials that survive the sifting process depends on the severity of the criteria used. At the start of sifting, the number of materials shown on the screen is the total in the database. As more restrictions are placed on the materials, the number of surviving materials gets smaller and could reach 0, i.e., no materials qualify. In such cases, some of the restrictions have to be relaxed and the sifting restarted.

8.2 Computer Assistance in Making Final Selection

Integrating material property database with design algorithms and computer-aided design (CAD)/computer-aided manufacturing (CAM) programs has many benefits including homogenization and sharing of data in the different departments, decreased redundancy of effort, and decreased cost of information storage and retrieval. Several such systems have been cited in Ref. 18, including:

- The Computerized Application and Reference System (CARS), developed from the AISI *Automotive Steel Design Manual*, performs first-order analysis of design using different steels.

- Aluminum Design System (ADS), developed by the Aluminum Association (U.S.), performs design calculations and conformance checks of aluminum structural members with the design specifications for aluminum and its alloys.
- Material Selection and Design for fatigue life predictions, developed by ASM International, aids in the design of machinery and engineering structures using different engineering materials.
- Machine Design's Materials Selection, developed by Penton Media (U.S.), combines the properties for a wide range of materials and the data set for design analysis.

8.3 Expert Systems

Expert systems, also called knowledge-based systems, are computer programs that simulate the reasoning of a human expert in a given field of knowledge. Expert systems rely on heuristics, or rules of thumb, to extract information from a large knowledge base. Expert systems typically consist of three main components:

- The knowledge base contains facts and expert-level heuristic rules for solving problems in a given domain. The rules are normally introduced to the system by domain experts through a knowledge engineer.
- The inference engine provides an organized procedure for sifting through the knowledge base and choosing applicable rules in order to reach the recommend solutions. The inference engine also provides a link between the knowledge base and the user interface.
- The user interface allows the user to input the main parameters of the problem under consideration. It also provides recommendations and explanations of how such recommendations were reached.

A commonly used format for the rules in the knowledge base is in the form:

IF (condition 1) and/or (condition 2)
THEN (conclusion 1)

For example, in the case of FRP selection:

IF: required elastic modulus, expressed in GPa, is more than 150 and specific gravity less than 1.7.
THEN: oriented carbon fibers at 60% by volume.

Expert systems are finding many applications in industry including the areas of design, trouble-shooting, failure analysis, manufacturing, materials selection, and materials substitution.[12] When used to assist in materials selection, expert systems provide impartial recommendations and are able to search large databases for optimum solutions. Another important advantage of expert systems is their ability to capture valuable expertise and make it available to a wider circle of users. An example is the Chemical Corrosion Expert System, which is produced by the National Association of Corrosion Engineers (NACE) in the United States.[18] The system prompts the user for information on the environmental conditions and configuration of the component and then recommends candidate materials.

REFERENCES

1. M. M. Farag, *Materials Selection for Engineering Design,* Prentice Hall Europe, London, 1997.
2. G. Dieter, "Overview of the Materials Selection Process," in *ASM Metals Handbook, Materials Selection and Design,* Vol. 20, Volume Chair George Dieter, ASM International, Materials Park, OH, 1997, pp. 243–254.
3. J. Clark, R. Roth, and F. Field III, "Techno-Economic Issues" in *ASM Metals Handbook, Materials Selection,* Vol. 20, Volume Chair George Dieter, ASM International, Materials Park, OH, 1997, pp. 255–265.
4. M. F. Ashby, "Materials Selection Charts," *ASM Metals Handbook,* Vol. 20, Volume Chair George Dieter, ASM International, Materials Park, OH, 1997, pp. 266–280.
5. M. F. Ashby, "Performance Indices," *ASM Metals Handbook,* Vol. 20, Volume Chair George Dieter, ASM International, Materials Park, OH, 1997, pp. 281–290.
6. D. Bourell, "Decision Matrices in Materials Selection," *ASM Metals Handbook,* Vol. 20, Volume Chair George Dieter, ASM International, Materials Park, OH, 1997, pp. 291–296.
7. T. Fowler, "Value Analysis in Materials Selection and Design," *ASM Metals Handbook,* Vol. 20, Volume Chair George Dieter, ASM International, Materials Park, OH, 1997, pp. 315–321.
8. F. A. Crane and J. A. Charles, *Selection and Use of Engineering Materials,* Butterworths, London, 1984.
9. M. F. Ashby, *Materials Selection in Mechanical Design,* Pergamon, London, 1992.
10. M. F. Ashby, *Mat. Sci. Tech.,* **5,** 517–525 (1989).
11. R. Sandstrom, "An Approach to Systematic Materials Selection," *Materials and Design,* **6,** 328–338 (1985).
12. V. Weiss, Computer-Aided Materials Selection, *ASM Metals Handbook,* Vol. 20, Volume Chair George Dieter, ASM International, Materials Park, OH, 1997, pp. 309–314.
13. P. A. Gutteridge and J. Turner, "Computer Aided Materials Selection and Design," *Materials and Design,* **3** (Aug), 504–510 (1982).
14. L. Olsson, U. Bengtson, and H. Fischmeister, "Computer Aided Materials Selection," in *Computers in Materials Technology,* T. Ericsson (ed.), Pergamon, Oxford, 1981, pp. 17–25.
15. P. P. Dargie, K. Parmeshwar, and W. R. D. Wilson, "MAPS 1: Computer Aided Design System for Preliminary Material and Manufacturing Process Selection," *Trans. ASME, J. Mech. Design,* **104,** 126–136 (1982).
16. M. M. Farag and E. El-Magd, "An Integrated Approach to Product Design, Materials Selection, and Cost Estimation," *Materials and Design,* **13,** 323–327 (1992).
17. S. Pugh, *Total Design: Integrated Methods for Successful Product Development,* Addison-Wesley, Reading, MA, 1991.
18. B. E. Boardman and J. G. Kaufman, Directory of Materials Properties Databases, Special Supplement to Advanced Materials & Processes, ASM International, Materials Park, OH, August 2000.
19. J. H. Westbrook, "Sources of Materials Property Data and Information," *ASM Metals Handbook,* Vol. 20, Volume Chair George Dieter, ASM International, Materials Park, OH, 1997, pp. 491–506.
20. D. Price, "A Guide to Materials Databases," *Materials World,* July, 418–421 (1993).
21. M. E. Heller, *Metal Selector*, ASM International, Materials Park, OH, 1985.