Material Selection & Acquisition

The ready availability of a wide variety of starting materials will greatly facilitate the realisation of a variety of products that can be manufactured. Knowledge of the range of readily available options will clearly be beneficial for the purposes of both designing and manufacturing these products and will help lead to optimal outcomes.

Project activities in which the material acquisition and selection are useful:

- Embodiment and Detailed Design
- Production Planning

Other tools that are useful in conjunction with the material acquisition and selection:

- Requirements Management

Introduction

Designers of a part typically specify the material composition and condition, while the manufacturer generally specifies the specific form of the starting material as well as its size. This tools is intended to provide a framework to help to organise the large amount of information required to form a sound basis for the selection and specification of appropriate starting materials for a mechanical design and manufacturing project.

The “in-house supplier” referred to in this document is represented by the University of Calgary Engineering Stores. The materials provided as examples are those typically available from Stores and can be requisitioned through the proper channels by students for use in course related projects.

Application of Material Acquisition

Stock Types

Materials can be categorised in a variety of ways. Most materials can be classified as follows:

- Bar, pipe, tube, structural sections
- Plate, sheet
- Hardware (e.g., screws, nuts, bolts, washers, electrical/plumbing fittings, etc.)
- Tooling (e.g., hand tools, cutters, drills, saw blades, etc.)
- Consumables (e.g., cleaning materials, cutting fluids, lubricants, first aid supplies, etc.)

Stock Specification

For the first two categories of stock types listed above, it will generally be necessary to specify four descriptors when a particular piece of material is required. The specification should contain the following information:

- **Composition –** what the piece of stock is made of
- **Shape** –the shape (often designating the cross-section) of the piece
- **Size** –the significant dimensions of the piece
- **Condition –** the metallurgical condition or some other descriptors

Below are listed some examples of the possibilities for each of the above information types.

Composition

There are a number of metal types (both ferrous and non-ferrous) which are available. There are also a number of plastics (both thermoplastics and thermosetting plastics) which are available. Alternate terms or some specific designations or trade names are included in parentheses.

- mild steel (low-carbon steel, AISI 1015)
- medium-carbon steel (AISI 1045)
- high-carbon steel (drill rob, music wire)
- tool steel (TOH)
- stainless steel (AISI 316)
- brass
- phenolic (fibre-reinforced)
- acrylic (Plexiglas, Lucite)
- molybdenum-filled nylon (Nylatron)
- AISI 4340
- leaded steel (AISI 12L14)
- 6061 Aluminium alloy
- copper
- acetal (Acetron, Delrin)
- nylon
- polycarbonate (Lexan)
- PTFE (Teflon)

Shape

It should be noted that not all shapes are available in all material types. Some shapes which some of the given materials are available are presented here.

Round bar

- mild steel
- stainless steel
- copper
- phenoli
- PTFE
- alloy steel
- brass
- aluminium alloy
- acetal

Square bar	• mild steel • aluminium alloy	• brass
Hexagonal bar	• mild steel	• brass
Rectangular bar	• mild steel • aluminium alloy	• brass • copper
Flat bar	• mild steel • aluminium alloy	• brass • copper

The following are also available but typically in a limited range of materials:

Round tube

Square tube

Rectangular tube

Pipe

(Note: The difference between round tube and pipe is reflected in the dimensioning thereof. Tubing is specified using the *outside dimension(s)* plus the *wall thickness*; pipe is specified using the *nominal inside dimension* and a *Schedule number*. A table sample of pipe dimensions is included as Attachment A).

Structural sections	• I-beam • equal angle • channel	• wide-flange beam • unequal angle • rectangular hollow

Plate

Sheet

(Note: The distinction between plate and sheet may be arbitrarily established on the basis of thickness. Plate will have a thickness greater than typically one-quarter to one-half inch. Sheet thickness will be less than the chosen figure. Thinner sheet metal will often be specified using a *Gauge*. A table of sheet thickness dimensions for a variety of gauges and applicability is included in Attachment B).

Size

The materials outlined above are typically specified using Imperial measure, which are typically expressed as either fractional or decimal inches. Section size increments vary:

increments are small for the smallest sizes (e.g., from 3/8”to 7/16”) and increase as the size increases (e.g., from 3-1/2” to 4”).

Standard lengths of bar, tube, and pipe are typically of the order of 20 feet.

The standard width for most of the available sheet and plate materials is 4 feet. Standard sheet and plate lengths range from 8 feet to 12 feet.

Condition

The condition of a given material as stocked can potentially include a number of factors – many of which arise as consequences of the way in which the material has been processed. Some examples are presented here along with some of the ramifications.

Cold- vs. hot-finished: several ferrous materials are available in- for example – either hot-rolled or cold-rolled condition. Factors which may differ include:

- size tolerances (smaller for cold-rolled version)
- surface finish (smoother for cold-rolled version)
- yield strength (higher for cold-rolled version)
- ductility (lower for cold-rolled version)
- residual stresses (higher for cold-rolled version)

Subsequent heat treatment (e.g., normalising) will further alter properties.

For wrought aluminium alloys, thermo-mechanical processing is indicated by a temper designation. For example, for 6061-T6 the temper designation T6 indicates that the alloy was solution-treated and artificially aged after forming. By way of contrast, 6061-O has been annealed and recrystallized and consequently has the lowest strength and the highest ductility in this condition.

Some other wrought materials such as brass or stainless steel sheet have been hardened through deformation alone; this is indicated by an –H1 designation. The degree of strain hardening is indicated using a second digit and can range from *quarter hard* (-H12) to *full hard* (-H18) condition. Many other temper designations exist and can be found in a variety of handbooks.

Using finishing processes of various types can also physically alter the condition of the material. For example, centerless grinding can be used to produce round bar having a very smooth finish and very small size tolerances. As an example, a couple of sample specifications, then, might be elaborated as follows:

i. 6 ft. of 2” X 1” 16 gauge 6061-T6511 rectangular tubing
ii. 2 ft. X 4 ft. X 1” HRMS plate

Cost Patterns

The cost of a given piece of material acquired will typically depend upon:

- the cost per unit dimension/volume/mass of the material;
- the amount of material required;
- scrap created; and
- cutting costs.

If the material is not available in-house and must be brought in from outside, additional considerations such as shipping costs, minimum order size, minimum billing, etc. may come into play.

Each of these factors may in turn depend upon a number of factors. For example,

- The cost per unit amount of material will depend upon the form, size, and condition of the material as well as the age of the material (what the price was when originally stocked). Consequently, the use of a $/kg figure may give only a very approximate guide to the cost of a given material. Cost figures for each material type, form, size and condition are generally available in a form similar to that in Attachment C.
- Amount of material required for the finished part may be considerably less than the amount that needs to be purchased. This can arise from the shape of the finished part, the amount of extra material needed for work-holding and so on. Another factor is the potential need to purchase a complete length of material as opposed to part of a length. This will typically arise when material must be brought in from an outside supplier.
- The material purchased but which does not end up as part of the finished product will likely constitute scrap. This may be as little as the amount of material lost during the initial cutting operation (e.g., the kerf created by a saw or cutting torch) or as much as 90% or more. Scrap will incur handling costs but may also have some recoverable value. In some instances, scrap may represent an elevated safety hazard and incur additional disposal costs.
- The cost of cutting the material will clearly depend upon the amount of material removed by the cutting operation as well as the cost of operating the cutting equipment. Actual cutting cost can be estimated by dividing the amount of material to be removed by the material removal rate (MRR) and multiplying by the cost/time of operating the equipment. Adding complexity to the cutting-off operation (by requiring a complicated cutting path, for example) can easily add to the cost of the operation. Purchase of a non-

standard quantity of material from external suppliers will typically incur a cutting charge.

While it may be possible to produce a very approximate estimate, the price of a given piece of material based upon a measure such as $/tonne, a more accurate estimate will require that many factors be considered.

Acquisition Logistics

While the acquisition of a particular piece of material may seem as simple as the purchase of an item of fast food, there are certain considerations that need to be addressed:

- Payment for materials for in-house materials can only be made from an approved account for which appropriate authorisation is made.
- If a cutting-off operation is required, the material may need to be moved to the appropriate machinery (saws, torches, shears, etc.), measured, the cutting operation set-up and then executed, and the remainder returned to the storage area. This may be a very simple operation as in the case of the material specified example (i) above, for instance. In the case of example (ii), however, if a full 4' X 10' plate of 1" steel needs to be moved, this will prove slightly more problematic (Hint: estimate the weight of both a full plate and the required piece of plate).

Application of Material Selection

The choice of material should allow *all part specifications to be met* while *minimizing the cost* of realising the product. This indicated that two information patterns would need to be elaborated:

1. the compatibility of a given piece of raw material with the specifications of the finished part; and
2. an expression used to model the total cost of the part.

If these two patterns are combined into the form of a quotient as shown below, it can be seen that maximizing the *numerator* while minimizing the *denominator* will yield a maximized quotient; this quotient can serve as a **Figure of Merit**..

[Fulfilment of Product Specifications]

÷

[Cost of Product Realisation]

Because it will be difficult or impossible to reduce the numerator to a single number in most instances, it will be necessary to examine the separate aspects of the product requirements and compile a multi-faceted numerator. For example, a part specification will often include requirements for shape, material content and condition, sizes/tolerance, surface finish, and so on. Each aspect of the specification can then be examined separately to establish the degree to which the product specification has been met.

The denominator will typically represent the sum of a number of cost factors including those outlined in the section above entitled "Cost Patterns" as well as the cost of subsequent processing requirements. It may be more appropriate, then to refer to the quotient as a **Function of Merit** in order to reflect its potential complexity and lack of inherent homogeneity. A more realistic quotient, then, might have the following appearance:

[{Shape Conformance}+{Material Conformance}+{Dimensional Conformance}+{Surface Conformance}+ …]

÷

[{Material Acquisition Cost}+{Subsequent Processing Cost (for shape, dimension, surface, etc.)}]

A search through the entire list of materials stocked using this test with reference to a particular part in order to select an optimum material would clearly be a lengthy, tedious, frustrating, costly and generally unsatisfactory process. It would be beneficial to rapidly narrow the options to a few good candidates and then systematically compare these few.

At this juncture, it is possible to introduce a heuristic or "rule –of –thumb" approach which will help to quickly narrow the search for an optimal solution. To do this, it is possible to employ some general (and perhaps obvious) observations.

Step 1 of the search will involve matching a closely as possible the material of the part and the composition of the material stock. Since there is usually very little or no scope for alteration of the material composition, an excellent match is usually required.

Step 2 of the search will typically involve selecting a form and size of the material stock that is most compatible with the product. Since most of the material costs are relatively modest when compared to the cost of processing in the workshop, situations can easily arise wherein even a relatively large increase in the cost of the starting material might result in a substantially decreased cost of the finished product by drastically reducing the processing component of the total cost.

From a casual scan of the two quotients shown below, it should be apparent that the second example appears to be a better choice than the first example.

Example 1:

[{50% Shape} + {100% Material} + {25% Dimension} + {0% Surface}]

÷

[{$10} + {$80 + $ 20 + $60}]

Example 2:

[{90% Shape} + {100% Material} + {90% Dimension} + {75% Surface}]

÷

[{$30} + {$10 + $ 5 + $25}]

The above example demonstrates that a three-fold increase in material cost still allows the total cost to be reduced by more than one-half.

The two step process outline above, then, can be reduced to the following rule-of-thumb:

Heuristic:

Choose a raw material that requires the minimum processing to achieve the product specification.

Since it should be apparent that it is necessary to project the sequence of processes needed to convert the starting material into the finished part before the Merit Function can be developed, the use of the heuristic approach allows some initial options to be selected without requiring detailed elaboration of the Merit Function (thereby reducing the cost of the decision process).

Other Considerations in Material Selection

Design Environments

Economic

The economic environment will define many aspects of material costs and can embrace issues ranging from purchasing through to recycling and disposal (e.g. consideration of scrap value or waste handling costs).

Product value can only be defined with at least some reference to the economic environment.

- **Cost of Material** will be dependent upon a large number of factors and can reflect costs of extraction/synthesis, energy of refining or initial processing, testing, shipping, storage, etc. Very small quantities or special requirements can often incur disproportionate costs depending upon the supply environment.

- **Life cycle costing** (LCC) includes selling price, operating cost, post-use cost.

Service/Use

All aspects of use must be considered; product failure can occur in a wide variety of modes - vulnerability to these can be influenced by the product composition. Some of the important categories of failure mode can be described as follows:

- **Inadequate assessment of environments.** A misreading of the economic environment, errors in assessment of loads to be sustained, failure to recognize the presence of (e.g. corrosive) agents deleterious to the product capabilities, or lack of awareness of the influence of manufacturing processes on material properties can all lead to product failure.
- **Incomplete characterisation of materials** can lead to selection of a material that will not function satisfactorily. Variability in strength parameters or susceptibility to environmental agents can easily lead to failure.
- **Modelling Errors** can result in mismatch between demands imposed on the materials used and the capability for the materials to meet these demands.
- **Inadequate maintenance, repair, service** can lead to a situation wherein the normal degradation of part attributes (through wear and tear) is allowed to progress to a stage where failures can be expected to occur.

Mechanical Loading/Failure Modes

1. Yield under static load
2. Buckling
3. Creep failure
4. Excessive Wear
5. Fracture due to static overload (ductile or brittle)
6. Fatigue
7. Stress corrosion cracking
8. Failure due to impact loading

Environmental Degradation

1. Electrochemical corrosion
2. Corrosion of plastics and ceramics
3. Oxidation
4. Wear/Erosion
5. Radiation damage

Legal Environment.

Design codes and standards are used to disseminate proven data and methods to designers without the capability to undertake design based upon fundamental principles. They are also used to ensure that acceptable design practices are followed in order to provide some assurance that failure can be avoided.

Product liability considerations may dictate the use of proven design codes and materials.

Manufacturing Environment

Manufacturability considerations can arise when manufacturing costs are influenced by material properties. This can occur in a wide variety of processing environments and can be exemplified by differences in machinability, joinability, deformability, or mouldability of different materials. For example, a free-machining steel may have a strength which is only slightly less than a similar steel but may involve very substantially lowered machining costs due to lower machining forces, superior machined surface finish, etc.

It is also important to recognize the importance of the particular manufacturing infrastructure that is accessible in influencing the ability to process different materials.

Manufacturability issues can also arise in connection with the potential influence of manufacturing operations on product properties or attributes. Some welding processes, for example, will greatly reduce the fatigue strength of some metals; similarly, cold deformation processes will often increase the yield strength of a metal while reducing its ductility.

MATERIAL CHARACTERIZATION

The characteristics of candidate materials will need to be sought. This process will be facilitated if the properties of the materials are readily accessible and organized in a systematic fashion. A number of references (including Ullman) provide data that is organized in a systematic fashion.

It should be recognized that material properties should be regarded as having some level of uncertainty. This can arise through a variety of factors including variability (or uncertainty) in the material specifications describing composition and processing. Statistical methods should be used to ensure that reasonable expectations of performance are anticipated.

If it were only necessary to optimize a single property, the selection process would be relatively straightforward. This situation rarely, if ever, prevails. The typical material selection problem involves optimizing the outcome of a number of competing requirements. Even a very simple problem can involve the requirement for a given level of functionality (as defined in the PDS) while minimizing cost. It becomes necessary, then, to examine the cost of achieving that function using a variety of approaches. This can sometimes be accomplished by looking at ratios of properties of candidate materials. Some examples might include Young's Modulus/density, Yield Strength/($\$/m^3$), K_{IC}/($/kg), some of which are referred to as the Cost per Unit Property Method.

Where many requirements exist, more elaborate selection/optimization methods include:

- Weighted properties method
- Limits on properties method
- Computer-aided material and process selection
- Expert systems

Attachment D provides selected items on material selection and acquisition. Attachment E provides selected examples of approaches to material selection – Simple Failure Avoidance, Cost per Unit Property Method, and Weighted Properties Method.

References

Faraq, M., *Materials Selection for Engineering Design*, Prentice-Hall, 1997.

Singh, Karambir, *Mechanical Design Principles: Applications, Techniques and Guidelines for Manufacture*, Nantel Publications, Melbourne, Australia, 1996. ISBN 0-646-25797-8 pp. 144-170.

Ullman, David G., *The Mechanical Design Process*, McGraw-Hill, U.S.A, 1997. pp. 199-200, 292-293.

Attachment A

Pipe Size Chart – Some Sample Values (inches)

"The size of all pipe is identified by the nominal pipe size. The manufacture of pipe in the nominal sizes of 1/8 inch to 12 inches, inclusive, is based on a standardized outside diameter (OD). This OD was originally selected so that pipe with a standard OD and having a wall thickness typical of the period would have an inside diameter (ID) approximately equal to the nominal size." (*Machinery's Handbook, 22nd ed.*)

Information from ANSI B36.10-1979 as presented in Machinery's Handbook, 22nd ed.

Nominal Size (in.)	O.D. (in.)	Wall Thickness	Schedule No.	Commercial Designation	Weight/foot (lb/ft)
1/8	0.405	0.068	40	STD	0.24
		0.095	80	XS	0.31
1/4	0.540	0.088	40	STD	0.42
		0.119	80	XS	0.54
3/8	0.675	0.091	40	STD	0.57
		0.126	80	XS	0.74
1/2	0.840	0.109	40	STD	0.85
		0.147	80	XS	10.9
		0.788	160	…	1.31
		0.294	…	XXS	1.71
3/4	1.050	0.113	40	STD	1.13
		0.154	80	XS	1.47
		0.219	160	…	1.94
		0.308	…	XXS	2.44
1	1.315	0.133	40	STD	1.68
		0.179	80	XS	2.17
		0.250	160	…	2.84
		0.358	…	XXS	3.66
1-1/4	1.660	0.140	40	STD	2.27
		0.191	80	XS	3.00
		0.250	160	…	3.76
		0.382	…	XXS	5.21
1-1/2	1.900	0.145	40	STD	2.72
		0.200	80	XS	3.63
		0.281	160	…	4.86
		0.400	…	XXS	6.41
2	2.375	0.783	…	…	2.03
		0.109	…	…	2.64
		0.125	…	…	3.00
		0.141	…	…	3.36
		0.154	40	STD	3.65
		…	…	…	…

Attachment B

Gauge Chart – Some Sample Values (inches)

GAUGE CHART - Some Sample Values (inches)

	Brass & Alumnium Sheet	Cold & Hot Rolled Steel Sheet	Aluminum, Brass, Copper, Steel Tube; Copper Sheet	Stainless Steel Sheet	Galvanized Steel Sheet
	Brown & Sharpe	Manuf'r's. Standard	Birmingham Wire Gauge	U.S. Standard	Galvanized Sheet Gauge
Gauge No.					
3	0.2294	0.2391	0.259		
4	0.2043	0.2242	0.238		
8	0.1285	0.1644	0.165	0.171875	0.1681
10	0.1019	0.1345	0.134	0.140625	0.1382
12	0.0808	0.1046	0.109	0.109375	0.1084
14	0.0641	0.0747	0.083	0.078125	0.0785
16	0.0508	0.0598	0.065	0.0625	0.0635
18	0.0403	0.0478	0.049	0.050	0.0516
20	0.0320	0.0359	0.035	0.0375	0.0396
22	0.0254	0.0299	0.028	0.03125	0.0336
24	0.0201	0.0239	0.022	0.025	0.0276
26	0.0159	0.0179	0.018	0.01875	0.0217

Attachment C

Examples of Available Material Stock & Prices

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ENGINEERING FACULTY STORES

HRS ROUND BAR

DESCRIPTION	SIZE	PER FT
HOT ROLLED STEEL - ROUND BAR	3/16"	0.12
HOT ROLLED STEEL - ROUND BAR Russel #27786	1/4"	~~0.10~~ .12
HOT ROLLED STEEL - ROUND BAR Russel #28788	5/16"	0.25
HOT ROLLED STEEL - ROUND BAR Russel #27790	3/8"	~~0.20~~ .24
HOT ROLLED STEEL - ROUND BAR	7/16"	~~0.25~~ .40
HOT ROLLED STEEL - ROUND BAR	1/2"	~~0.30~~ .35
HOT ROLLED STEEL - ROUND BAR Russel #27656	3/4"	~~0.65~~ .70
HOT ROLLED STEEL - ROUND BAR	7/8"	0.85
HOT ROLLED STEEL - ROUND BAR Russel #27706	1"	~~1.00~~ 1.20 ~~1.15~~ ~~1.49~~
HOT ROLLED STEEL - ROUND BAR	1 1/4"	2:05
HOT ROLLED STEEL - ROUND BAR # 27762	1 1/2"	2.60

HRS SQUARE BAR

DESCRIPTION	SIZE	PER FT
HOT ROLLED STEEL - SQUARE BAR #27866	1/2"	0.30
HOT ROLLED STEEL - SQUARE BAR #27870	3/4"	1.00
HOT ROLLED STEEL - SQUARE BAR #27876	1"	1.65

HRS FLAT BAR

DESCRIPTION	SIZE	PER FT
HOT ROLLED STEEL - FLAT BAR	1/8" x 1/2"	~~0.40~~ .25
HOT ROLLED STEEL - FLAT BAR	1/8" x 3/4"	0.25
HOT ROLLED STEEL - FLAT BAR #00548	1/8" x 1"	~~0.26~~ .30
HOT ROLLED STEEL - FLAT BAR	1/8" x 1 1/4"	0.35
HOT ROLLED STEEL - FLAT BAR	1/8" x 1 1/2"	0.40
HOT ROLLED STEEL - FLAT BAR #00556	1/8" x 2"	0.49
HOT ROLLED STEEL - FLAT BAR	1/8" x 2 1/2"	0.60
HOT ROLLED STEEL - FLAT BAR #00560	1/8" x 3"	0.75
HOT ROLLED STEEL - FLAT BAR #00564	1/8" x 4"	0.90

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HRS FLAT BAR

DESCRIPTION	SIZE	PER FT
HOT ROLLED STEEL - FLAT BAR	3/16" x 1/2"	0.15
HOT ROLLED STEEL - FLAT BAR	3/16" x 3/4"	0.30
HOT ROLLED STEEL - FLAT BAR # 00582	3/16" x 1"	~~0.30~~ ~~.35~~ .40
HOT ROLLED STEEL - FLAT BAR	3/16" x 1 1/4"	0.50
HOT ROLLED STEEL - FLAT BAR	3/16" x 1 1/2"	0.50
HOT ROLLED STEEL - FLAT BAR #00590	3/16" x 2"	~~0.50~~ .70
HOT ROLLED STEEL - FLAT BAR #00598	3/16" x 3"	0.95
HOT ROLLED STEEL - FLAT BAR	1/4" x 1/2"	0.25
HOT ROLLED STEEL - FLAT BAR	1/4" x 3/4"	0.40
HOT ROLLED STEEL - FLAT BAR #37140	1/4" x 1"	~~0.40~~ .45
HOT ROLLED STEEL - FLAT BAR	1/4" x 1 1/4"	~~0.45~~ .60
HOT ROLLED STEEL - FLAT BAR	1/4" x 1 1/2"	0.65
HOT ROLLED STEEL - FLAT BAR #37002	1/4" x 2"	~~0.75~~ .80
HOT ROLLED STEEL - FLAT BAR	1/4" x 3"	~~1.00~~ 1.15
HOT ROLLED STEEL - FLAT BAR #37170	~~1/4" x 4"~~	1.50 ~~1.30~~ ~~2.15~~
HOT ROLLED STEEL - FLAT BAR	1/4" x 6"	~~1.70~~ 2.15
HOT ROLLED STEEL - FLAT BAR	1/4" x 8"	2.80
~~HOT ROLLED STEEL - FLAT BAR~~	~~1/4" x 10"~~	~~2.30~~
~~HOT ROLLED STEEL - FLAT BAR~~	~~1/4" x 12"~~	~~2.40~~
HOT ROLLED STEEL - FLAT BAR	3/8" x 1"	~~0.55~~ .60
HOT ROLLED STEEL - FLAT BAR	3/8" x 1 1/4"	0.75
HOT ROLLED STEEL - FLAT BAR	3/8" x 1 1/2"	~~0.95~~ 1.00
HOT ROLLED STEEL - FLAT BAR	3/8" x 2"	1.05
HOT ROLLED STEEL - FLAT BAR	3/8" x 2 1/2"	1.50
HOT ROLLED STEEL - FLAT BAR	3/8" x 3"	1.90
HOT ROLLED STEEL - FLAT BAR	3/8" x 4"	~~1.80~~ 2.25
HOT ROLLED STEEL - FLAT BAR	3/8" x 6"	~~2.60~~ 3.35

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ENGINEERING FACULTY STORES

1/16 Welding Rod .15 ea
1/8 " " .30 ea

CRS ROUND BAR

DESCRIPTION	SIZE	PER FT	
COLD ROLLED STEEL - ROUND BAR	1/8"	0.10	N.L.A.
COLD ROLLED STEEL - ROUND BAR	3/16"	0.12	
COLD ROLLED STEEL - ROUND BAR	1/4"	0.15	
COLD ROLLED STEEL - ROUND BAR	5/16"	~~0.20~~	.25
COLD ROLLED STEEL - ROUND BAR	3/8"	~~0.30~~	.35
COLD ROLLED STEEL - ROUND BAR	7/16"	0.45	.45
COLD ROLLED STEEL - ROUND BAR	1/2"	~~0.40~~	~~.50~~ .55
COLD ROLLED STEEL - ROUND BAR	5/8"	0.95	
COLD ROLLED STEEL - ROUND BAR	3/4"	0.90	
COLD ROLLED STEEL - ROUND BAR	7/8"	~~1.30~~	1.60
COLD ROLLED STEEL - ROUND BAR	1"	~~1.60~~	1.80
COLD ROLLED STEEL - ROUND BAR	1 1/8"	2.00	
COLD ROLLED STEEL - ROUND BAR	1 1/4"	3.80	
COLD ROLLED STEEL - ROUND BAR	1 1/2"	4.55	
COLD ROLLED STEEL - ROUND BAR	1 5/8"	5.55	
COLD ROLLED STEEL - ROUND BAR	1 3/4"	4.85	
COLD ROLLED STEEL - ROUND BAR	1 7/8"	7.10	
COLD ROLLED STEEL - ROUND BAR	2"	10.05 ~~6.80~~	
COLD ROLLED STEEL - ROUND BAR	2 1/4"	9.80	
COLD ROLLED STEEL - ROUND BAR	2 1/2"	11.40	
COLD ROLLED STEEL - ROUND BAR	2 3/4"	18.00	
COLD ROLLED STEEL - ROUND BAR	3"	22.00	
COLD ROLLED STEEL - ROUND BAR	3 1/2"	29.60	
COLD ROLLED STEEL - ROUND BAR	4"	56.30 ~~48.75~~	56.30
COLD ROLLED STEEL - ROUND BAR	4 1/2"	81.35 ~~58.00~~	
COLD ROLLED STEEL - ROUND BAR	5"	63.00	
COLD ROLLED STEEL - ROUND BAR	6"	74.00	

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ENGINEERING FACULTY STORES

CRS SQUARE BAR

DESCRIPTION	SIZE	PER FT	
COLD ROLLED STEEL - SQUARE BAR	1/8"	~~0.22~~	.25
COLD ROLLED STEEL - SQUARE BAR	3/16"	0.25	
COLD ROLLED STEEL - SQUARE BAR	1/4"	~~0.25~~	.30
COLD ROLLED STEEL - SQUARE BAR	5/16"	0.35	
COLD ROLLED STEEL - SQUARE BAR	3/8"	~~0.60~~	.45
COLD ROLLED STEEL - SQUARE BAR	7/16"	1.30	
COLD ROLLED STEEL - SQUARE BAR	1/2"	0.85	
COLD ROLLED STEEL - SQUARE BAR	5/8"	~~0.95~~	1.25
COLD ROLLED STEEL - SQUARE BAR	3/4'	~~1.65~~	2.00
COLD ROLLED STEEL - SQUARE BAR	7/8"	3.20	
COLD ROLLED STEEL - SQUARE BAR	1"	4.70	
COLD ROLLED STEEL - SQUARE BAR	1 1/8"	3.80	
COLD ROLLED STEEL - SQUARE BAR	1 1/4"	4.10	
COLD ROLLED STEEL - SQUARE BAR	1 3/8"	5.75	
COLD ROLLED STEEL - SQUARE BAR	1 1/2"	7.60	
COLD ROLLED STEEL - SQUARE BAR	1 3/4"	14.00	
COLD ROLLED STEEL - SQUARE BAR	1 7/8"	12.65	
COLD ROLLED STEEL - SQUARE BAR	2"	12.75	
COLD ROLLED STEEL - SQUARE BAR	2 1/4"	16.15	
COLD ROLLED STEEL - SQUARE BAR	2 1/2"	37.20	
COLD ROLLED STEEL - SQUARE BAR	3"	32.75	

PRICES & STOCK ARE SUBJECT TO CHANGE WITHOUT NOTICE

Attachment D

Selected Information on Material Acquisition & Selection

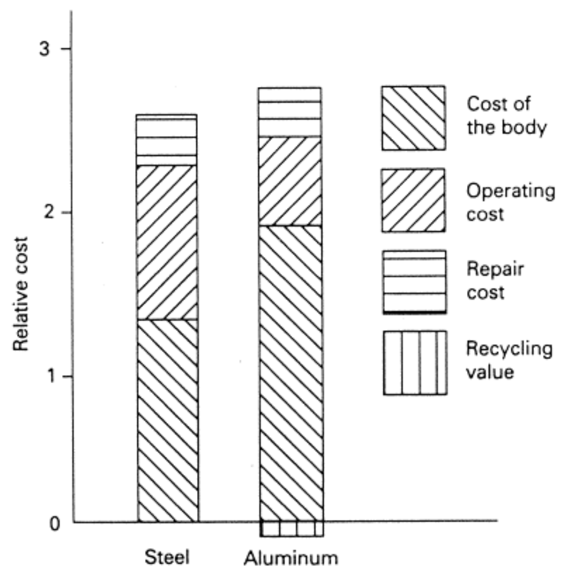


Figure 1.11 Life cycle cost comparison of steel and aluminum in motor car body. (Based on figures by Dieffenbach and Mascarin 1993.)

Table 1.3 Energy used for production of some engineering materials

Metal	Primary metal		Secondary metal	
	GJ/ton	%	GJ/ton	% of primary metal
Mg	370	100	10	2.7
Al	350	100	15	4.3
Ni	150	100	15	10
Cu	120	100	20	17
Zn	70	100	20	29
Pb	30	100	10	33
Steel	35	100	15	43

Source: *Metals handbook, desk edition*, ASM, Metals Park, Ohio, 1985, p 31.5.

Table 1.4 Comparison of costs involved in manufacture of 355 ml container (in cents) in 1987, based on Berry (1992)

Cost element	Al	Glass	Plastic	Steel
Raw material	4.6	1.70	1.71	3.18
Manufacturing cost	3.19	7.80	6.27	3.81
Distribution cost	0.05	0.50	0.05	0.08
Recycling credit	(1.29)	(2.25)	(0.00)	(0.33)
Total net cost	6.55	7.75	8.03	6.74

Table 9.1 Formulas for estimating cost per unit property

Cross-section and loading conditions	Cost of unit strength	Cost of 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	$C\rho/S$	–

S = working yield strength of the material, C = cost per unit mass, ρ = density, E = Young's modulus, G = shear modulus.

Table 9.2 Characteristics of candidate materials for the beam

Material	Working stress[a] (MPa)	Working stress[a] (ksi)	Specific gravity	Relative cost[b]	Cost of unit strength
Steel AISI 1020, normalized	117	17	7.86	1	0.73
Steel AISI 4140, normalized	222	32	7.86	1.38	0.73
Aluminum 6061, T6 temper	93	13.5	2.7	6	1.69
Epoxy + 70% glass fibers	70	10.2	2.11	9	2.26

[a] The working stress is computed from yield strength using a factor of safety of 3.
[b] The relative cost per unit weight is based on AISI 1020 steel as unity. Material and processing costs are included in the relative cost.

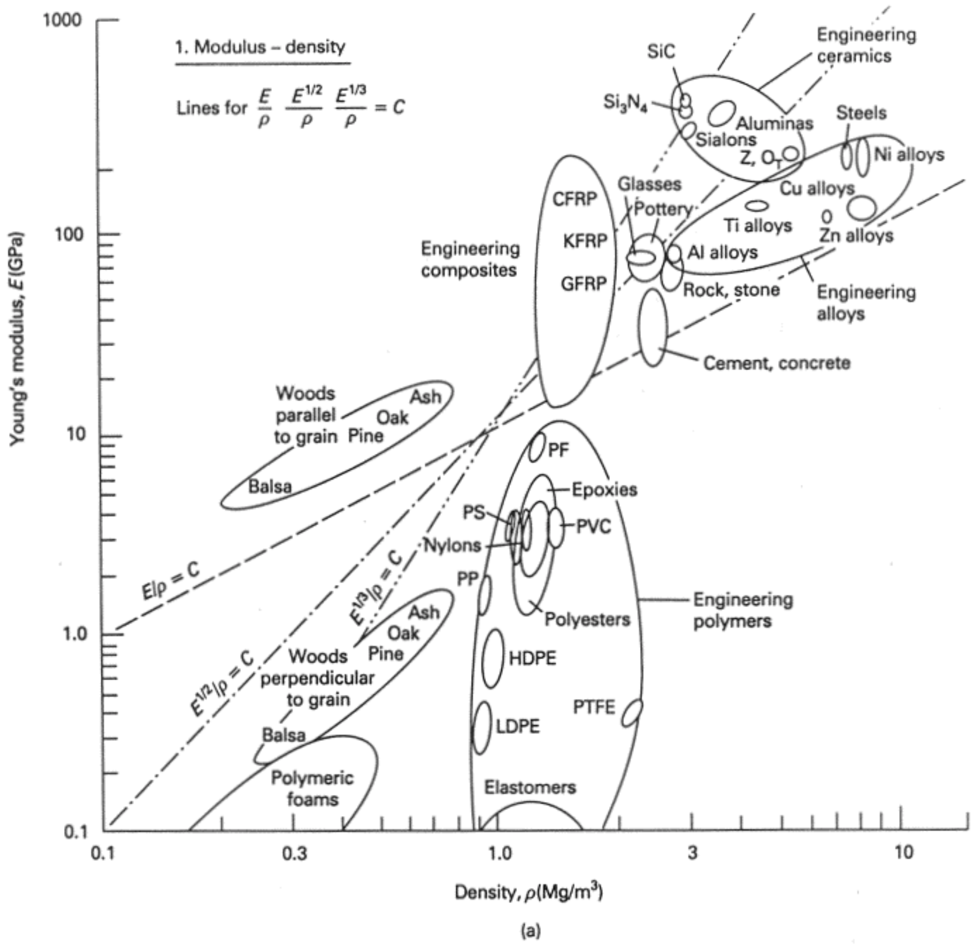
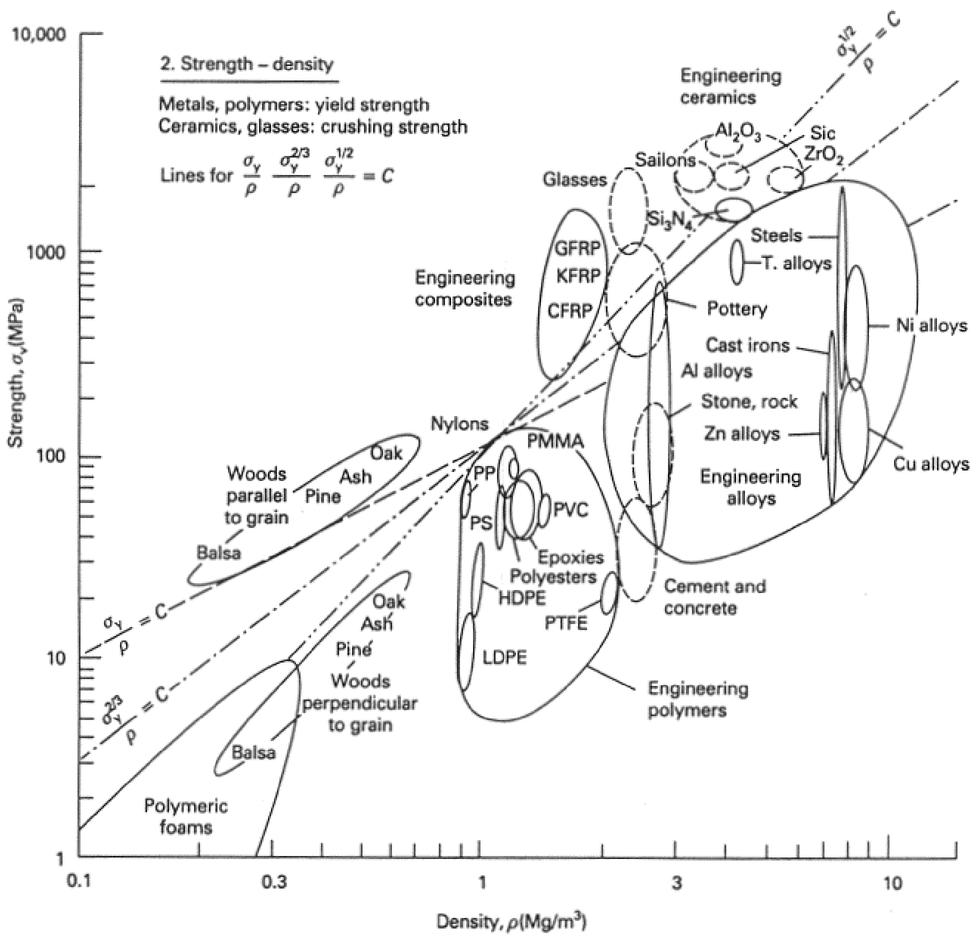


Figure 9.1 An example of Ashby's materials selection chart. (a) Elastic modulus vs. density. (b) Strength vs. density. From *Materials Science and Technology*, vol. 5, 1989, pp. 517–525.



2. Strength – density
Metals, polymers: yield strength
Ceramics, glasses: crushing strength
Lines for $\frac{\sigma_y}{\rho}$ $\frac{\sigma_y^{2/3}}{\rho}$ $\frac{\sigma_y^{1/2}}{\rho} = C$
Engineering ceramics
Al_2O_3
Sic
ZrO_2
Sailons
Glasses
Si_3N_4
Steels
T. alloys
GFRP
KFRP
CFRP
Engineering composites
Pottery
Ni alloys
Cast irons
Al alloys
Stone, rock
Zn alloys
Cu alloys
Engineering alloys
Nylons
PMMA
Oak
Ash
Pine
Woods parallel to grain
Balsa
PP
PS
PVC
Epoxies
Polyesters
HDPE
PTFE
LDPE
Cement and concrete
Engineering polymers
Woods perpendicular to grain
Polymeric foams
$\frac{\sigma_y}{\rho} = C$
$\frac{\sigma_y^{2/3}}{\rho} = C$
$\frac{\sigma_y^{1/2}}{\rho} = C$
Strength, σ_y(MPa)
Density, ρ(Mg/m^3)
10,000
1000
100
10
1
0.1
0.3
3
10

Table 9.6 Properties of candidate materials for cryogenic tank

Material	1 Toughness index[a]	2 Yield strength (MPa)	3 Young's modulus (GPa)	4 Specific gravity	5 Thermal expansion[b]	6 Thermal conductivity[c]	7 Specific heat[d]
Al 2014–T6	75.5	420	74.2	2.8	21.4	0.37	0.16
Al 5052–O	95	91	70	2.68	22.1	0.33	0.16
SS 301–FH	770	1365	189	7.9	16.9	0.04	0.08
SS 310–3/4H	187	1120	210	7.9	14.4	0.03	0.08
Ti–6Al–4V	179	875	112	4.43	9.4	0.016	0.09
Inconel 718	239	1190	217	8.51	11.5	0.31	0.07
70Cu–30Zn	273	200	112	8.53	19.9	0.29	0.06

[a] Toughness index, TI, is based on UTS, yield strength YS, and ductility e, at −196°C (−321.8°F). TI = (UTS + YS)e/2.
[b] Thermal expansion coefficient is given in 10^{-6}/°C. The values are averaged between RT and −196°C.
[c] Thermal conductivity is given in cal/cm^2/cm/°C/s.
[d] Specific heat is given in cal/g/°C. The values are averaged between RT and −196°C.

Table 9.8 Cost, figure of merit, and ranking of candidate materials

Material	Relative cost[a]	Cost of unit strength × 100	Performance index	Figure of merit	Rank
Al 2014–T6	1	0.67	42.2	62.99	2
Al 5052–O	1.05	3.09	40.1	12.98	6
SS 301–FH	1.4	0.81	70.9	87.53	1
SS 310–3/4H	1.5	1.06	50.0	47.17	3
Ti–6Al–4V	6.3	3.20	59.8	18.69	4
Inconel 718	5.0	3.58	53.3	14.89	5
70 Cu–30 Zn	2.1	8.96	35.9	4.01	7

[a] The costs include stock material and processing cost. The relative cost is obtained by considering the cost of Al 2014 as unity and relating the cost of other materials to it.

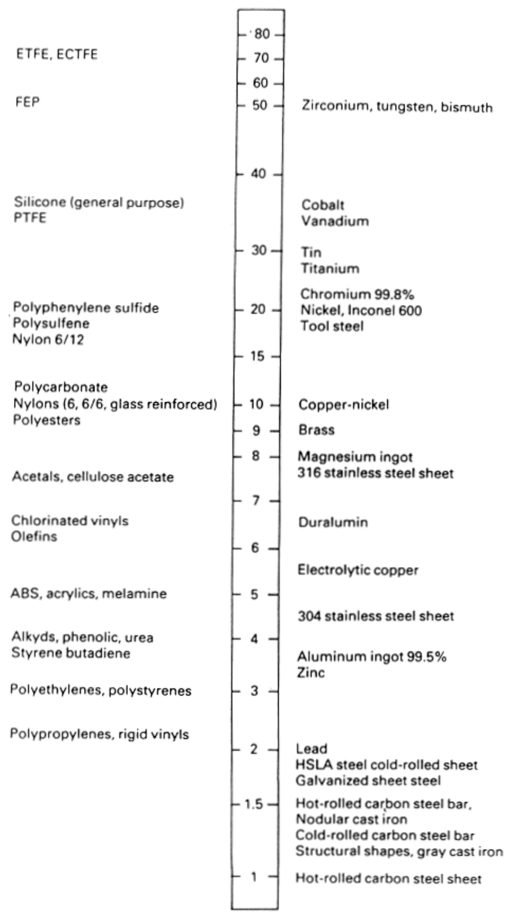


Figure 8.2 Comparison of some engineering materials on the basis of cost per unit mass. Comparison is made relative to the cost of hot-rolled low-carbon steel sheet.

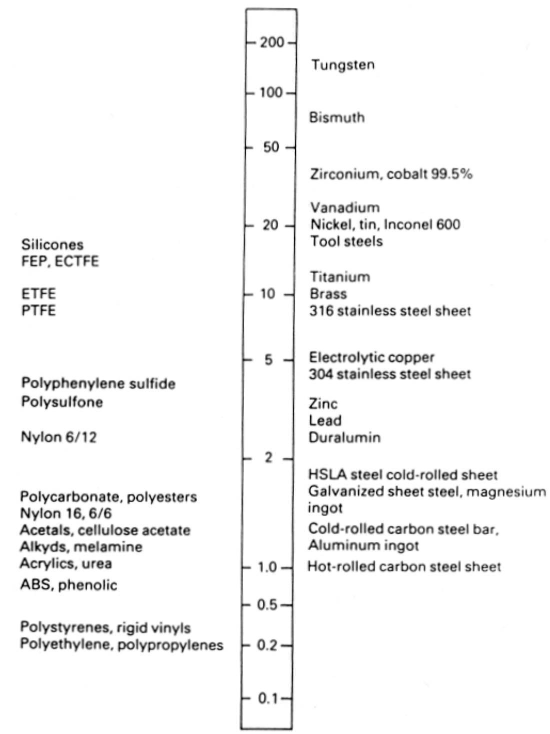


Figure 8.3 Comparison of some engineering materials on the basis of cost per unit volume. Comparison is made relative to the cost of hot-rolled low-carbon steel sheet.

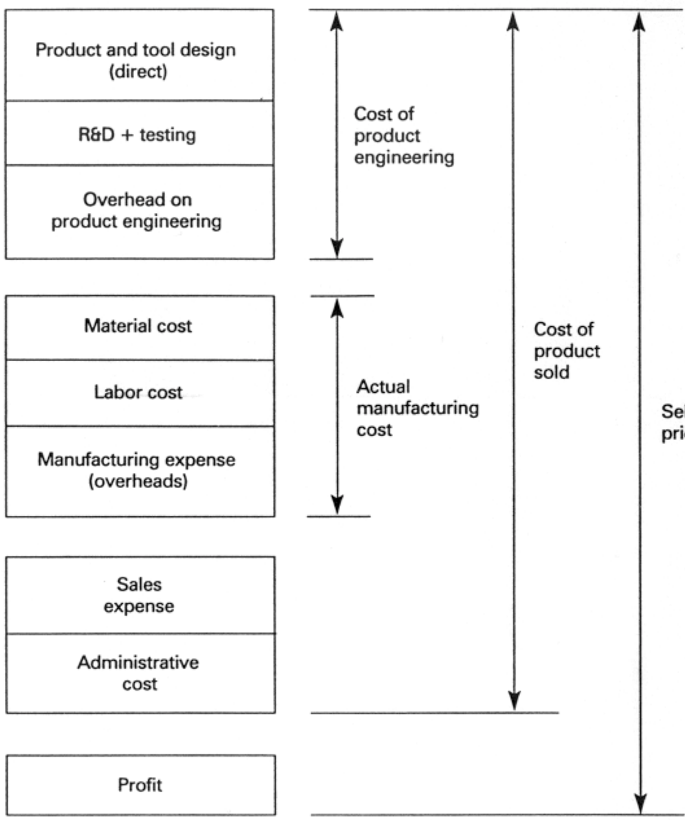


Figure 1.4 Factors involved in determining the selling price of a product.

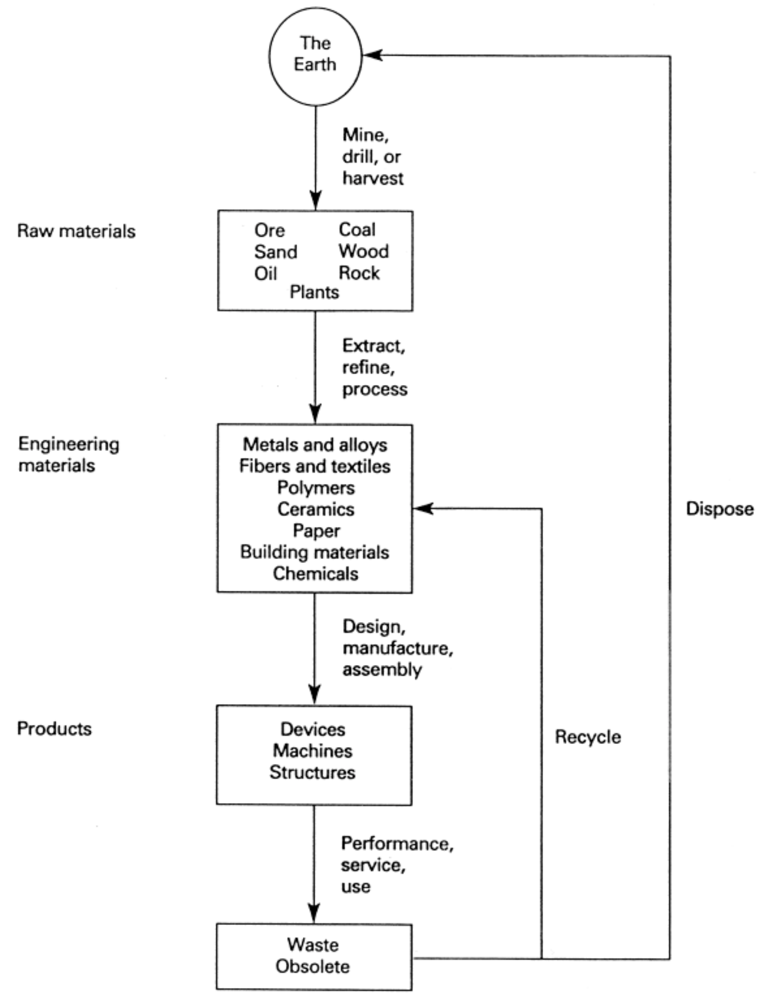


Figure 1.8 The place of recycling in the total material cycle.

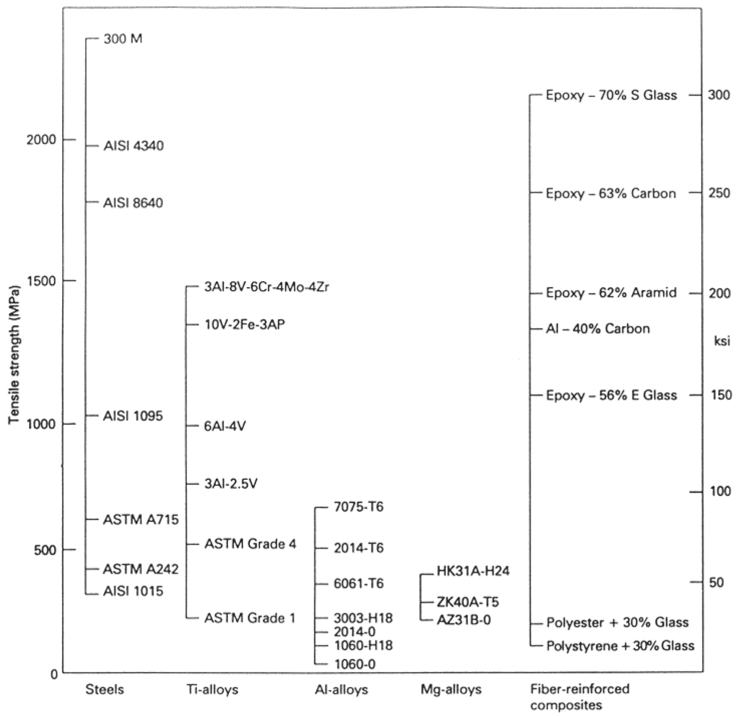


Figure 4.1 Comparison of some engineering materials on the basis of tensile strength.

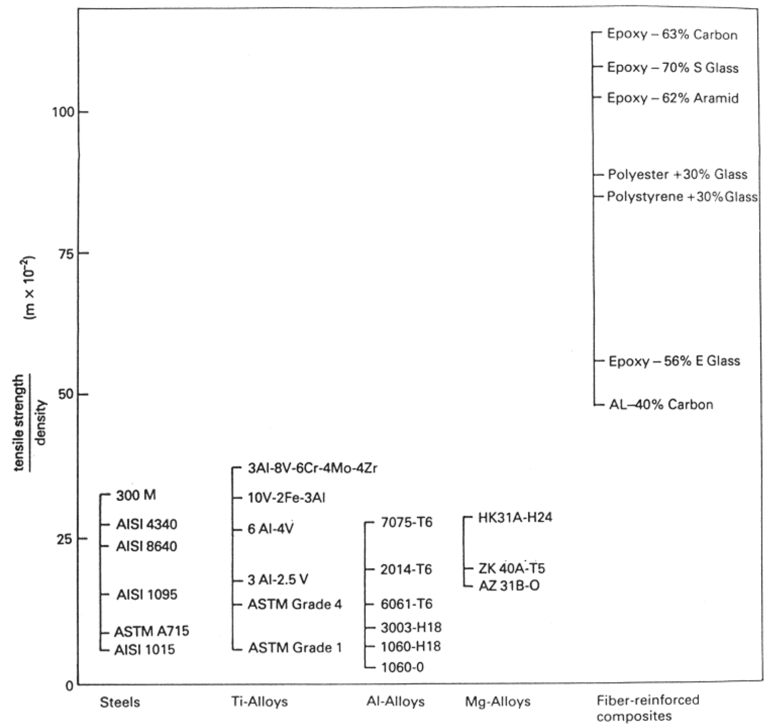


Figure 4.2 Comparison of some engineering materials on the basis of specific tensile strength.

Attachment E

Examples of Approaches to Material Selection

References: These notes are based on Farag, M., *Materials Selection for Engineering Design*, Prentice-Hall, 1997.

Approach 1 - Simple Failure Avoidance

Selection of material to resist failure due to static axial load and subject to configuration constraints (after Farag[1] - Example 4.1).

Example 1: A load of 50 kN is to be supported on cylindrical strut 200 mm long. Maximum strut diameter is 20 mm. Maximum strut mass is 0.25 kg. Which of the following materials is (best) suited for the strut?

Material	Strength (Mpa)	Elastic Modules (Gpa)	S.G.	Diameter (strength) (mm)	Diameter (buckling) (mm)	Mass[1] (kg)	Remarks
ASTM A675 Gr 45	155	211	7.8	20.3	15.75		Reject (1)
ASTM A675 Gr 80	275	211	7.8	15.2	15.75	0.3	Reject (2)
ASTM 717 Gr 80	550	211	7.8	10.8	15.75	0.3	Reject (2)
AA 2014-T6	420	70.8	2.7	12.3	20.7		Reject (1)
Nylon 6/6	84	3.3	1.14	27.5	44.6		Reject (1)
Epoxy -70% glass	2100	62.3	2.11	5.5	21.4		Reject (1)
Epoxy - 62% Kevlar	1311	82.8	1.38	7.0	19.9	0.086	Accept

[1] - Mass is calculated based upon larger value of diameter.
Reject (1) - diameter limit violated; **Reject (2)** - mass limit violated.

Approach 2 - Cost per unit property method.

Selection of material to resist failure through plastic deflection while minimizing cost (after Farag - Case Study 9.1).

Example 2: A simply-supported beam with solid rectangular cross-section and a width of 100 mm is to span 1 m and support a concentrated load of 20 kN acting vertically at the centre of the span. Which of the materials listed below would be the least expensive?

Cost per unit strength for a solid rectangle in bending is:

$$C\rho / S^{1/2}$$

where: **C** is (total) cost/unit mass *[can be Life Cycle Cost (LCC) which includes such costs as handling, manufacturing, recycling, etc.]*
ρ is material density
S is working stress of material

(Why is the strength reduced by an exponential? *It indicates the efficiency of material utilization for the particular loading situation.*)

Material	Working Stress[1] (Mpa)	S.G.	Relative Cost[2]	Cost of unit Strength
AISI 1020, normalized	117	7.86	1	0.73
AISI 4140, normalized	222	7.86	1.38	0.73
6061 - T6 Aluminum	93	2.7	6	1.69
Epoxy + 70% glass	70	2.11	9	2.26

[1] - Yield strength / 3
[2] - Relative to AISI 1020 (Material and processing cost included in relative cost)

Which would be the optimum material if the stiffness rather than the strength is the prime functional requirement and if the cost per unit stiffness for a solid rectangle in bending is $C\rho/E^{1/3}$ (E = Young's modulus)?

Approach 3 - Weighted properties method (after Farag[1] - Section 9.6)

When a number of (potentially competing) functional requirements must be satisfied it is sometimes possible to assign relative importance (expressed as a weighting factor α) to the different material properties associated with the different functional requirements.

Since different material properties are often expressed in different units or even in terms of relative merit, (e.g. machinability, corrosion resistance) it will often be necessary to rationalize or scale the various property measurements. Scaling can be done by assigning a value of 100 to the best property value available and then calculating the scaled values for the alternate materials as follows:

B = scaled property = (numerical value of property $\times$ 100) / (maximum value in list)

While this equation is appropriate where the maximum value for the property has the greatest merit (e.g. strength, etc.), there are some properties where the minimum value will have the greatest merit (e.g. cost, density). For these properties, then:

B = scaled property = (minimum value in the list $\times$ 100) / (numerical value of property)

Where numerical property values are not available or relevant, numerical values can be assigned based upon an arbitrary scale.

The relative merit of the candidate materials with respect to all functional requirements, then, can be assessed by calculating a performance index (γ) for all candidate materials and determining which material has the highest value.

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