TEACHING MATERIALS AND PROCESS SELECTION TO MECHANICAL ENGINEERING STUDENTS

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Introduction

Mechanical engineers are often faced with the problem of selecting the best possible material and the best manufacturing process for making a designed product using the material. One good approach to achieve this purpose would be to examine alternative materials available for making the product and choosing the best material based on the product service requirements. Once this is done, the alternate processes available for making the product using this material may then be considered and the best process chosen based on the technological and economic feasibilities of the process. Unfortunately this exercise is seldom simple on account of the enormous progress in the development of materials and processes in recent times [1]. Fortunately, the monumental work done by Ashby and his associates [2] has paved the way for not only making these tasks simpler, but provide unambiguous guidelines for completing these tasks. A course with examples highlighting these aspects would be of great benefit to mechanical engineering students in learning how to apply the knowledge in their profession. This paper was written as a preamble for this goal.

In this paper the bicycle frame was chosen as the principal designed product for several reasons. The primary reason is that the frame is a highly evolved mechanical structure [3] for which numerous materials are used depending on the service requirements. The other reasons include easy access to bicycles, familiarity with the features and the enormous public interest in the field as evident from the internet search engines [e.g. 4]. Investigation of the reasons for the choice of the material(s) in each case and the processes suitable for making the frame out of them would provide an exciting opportunity for mechanical engineering students to learn how to link product functional requirements with materials and processes in a rational manner.

The CES 4.5 (Cambridge Engineering Selector, version 4.5) software package [8] developed by Ashby and his associates and licensed by Granta Design Limited [5] was used by the author as the basis for this paper. This software provides structured data on many materials and processes of current interest. If this software is used in conjunction with the book by Ashby [2] it is possible to take a tour of the exciting world of materials and processes and get to know the features of each and their interaction in a highly focused manner. It is the hope of this author that this paper will serve as a nucleus for developing formal courses on these lines to benefit students.

The Bicycle Frame

For the purpose of this paper several simplifying assumptions are made as follows:

1. The bicycle fork is selected as a representative member of the frame.
2. The fork is made from tubing of uniform cross section along its length and is treated as a beam subjected to bending.
3. The curvature in the fork is neglected.
4. The material and the cross sectional area used for fork are variable but its length and thickness are fixed.
5. The constraint for material selection depends on the purpose for which the bicycle used.
6. The fracture toughness of the fork material should exceed 15 MPa $m^{1/2}$
7. The objective is to minimize the mass of the fork.

Bicycles are used for different purposes such as cheap transportation, racing and hiking. The materials and processes suited to each type will be examined in this paper, as suggested in a course by Ashby [6].

Material Selection

Material Indices

The material indices depend on the constraints such as cost, strength and stiffness. The procedure for deriving the latter two is outlined below. It is assumed that the objective is to minimize the mass.

Material Index for Light, Stiff Hollow Beam

If it is assumed that the fork has a mass m, length L, area of cross section A and density ρ, then,

$$m = AL\rho \qquad (1)$$

The bending stiffness S is given by

$$S = (C_1 EI) / L^3 \qquad (2)$$

where, C_1 is a constant depending on the type of load, E is the Young's modulus and I is the moment of inertia. For a hollow tubular beam, A is nearly equal to 2 π r t and I is nearly equal to π r^3 t, where r is internal radius and t is the section thickness. If we assume that only the radius of the tube is free to change but the thickness remains constant, then by eliminating r in equations (1) and (2),

$$M_1 = E^{1/3} / \rho \qquad (3)$$

where, M_1 is the material index for that needs to be maximized for minimum mass of the hollow beam with a given stiffness.

Material Index for Light, Strong Hollow Beam
It is again assumed that the radius is free to change while the thickness remains constant. If σ is assumed to be the strength of the material, then the failure load of the beam is given by

$$F = (C_2 Z) / L \quad (4)$$

where C_2 is a constant and Z is section modulus, which for the hollow beam is almost equal to $\pi r^2 t$. Again eliminating r from equations (1) and (4),

$$M_2 = \sigma^{1/2} / \rho \quad (5)$$

It is to be noted that equations (3) and (5) are different from those derived for square sectioned solid beams by Ashby [7].

Material Index for a Cheap, Strong Hollow Beam
It is necessary to minimize the cost in this case. The procedure is similar to that followed for the strong hollow beam except that the factor

$$C = A\ L\ \rho\ C_m \quad (6)$$

has to be minimized instead of the mass. Here, C_m is the cost of the material for unit mass. It follows that the new material index is

$$M_3 = \sigma^{1/2} / \rho C_m \quad (7)$$

Equations (3), (5), and (7) are applicable to a racing bicycle, hiking (mountain) bicycle and cheap transportation bicycle respectively.

Material Selection Using Ashby's Charts.
The procedure adopted for constructing Ashby's bubble chart and material evaluation using the gradient (slope) method is based on the instructions provided in reference [8]. Instructions in a condensed form are also provided in reference [9] available from reference [5].

Racing Bicycle
In Fig. 1 is shown a bubble chart of Elastic Modulus versus Density for several materials as available in CES 4.5 [8] Edu Level 2 package. For this purpose, the 'graph stage' is selected, density is assigned to x-axis and elastic modulus to the y-axis, a limit of 15 MPa-$m^{1/2}$ is set for the fracture toughness of the material and a bubble chart of Elastic Modulus versus Density for the qualifying materials is constructed. Consistent with the index of 1/3 for E in equation (3) a straight line with a slope of 3 is selected on this chart, based on the following rationale. Considering equation (3) and taking logarithm on both sides,

$$\log M_1 = 1/3(\log E) - \log \rho$$
$$or \qquad (8)$$
$$\log E = 3(\log M_1) + 3\log \rho$$

The above equation represents a straight-line relationship between log E and $\log \rho$ with a slope of 3 and an intercept of 3($\log M_1$). Each parallel straight line drawn with a slope of 3 (using a 'line selection' in the graph stage and assigning a value of 3 for the slope) in a bubble chart of $\log E$ versus $\log \rho$ intersects materials with a particular M_1, the material index derived using equation (3).

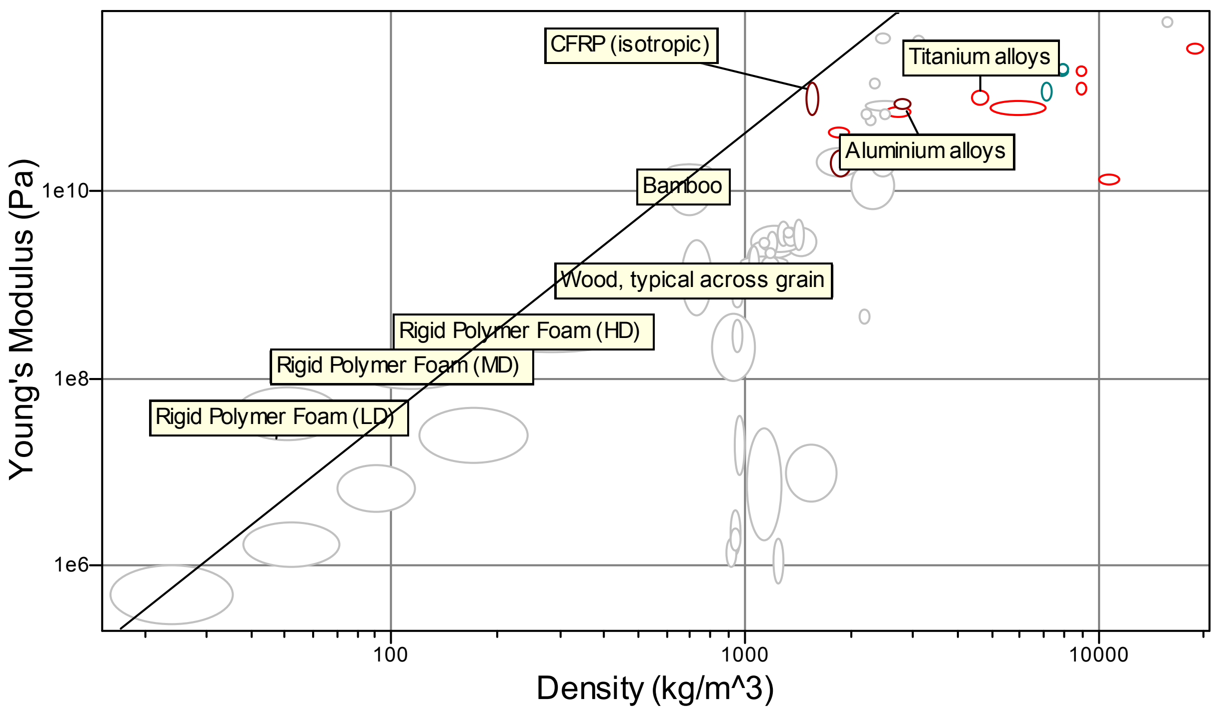

Fig.1. Young's Modulus vs. Density Chart for Light, Stiff Hollow Beam

A straight line parallel to the one shown in the figure passing through the top of the bubble for titanium alloys has a slope of 3 and an M_1 value of about 1.1. In contrast parallel lines drawn through the top of the bubble for aluminum alloys shows an M_1 value of about 1.7 and the line shown, drawn through the top of the CFRP bubble, has an M_1 value of about 3.5, indicating that for this design the stiffest CFRP is the best material followed by stiffest aluminum alloys and then by stiffest titanium alloys. Though materials like rigid polymer foam, boron carbide and wood have high M_1 values, they are to be excluded on account of their fracture toughness values being lower than 15 MPa $m^{1/2}$. Low alloy steel falls below titanium alloys, having a maximum M_1 value of about 0.8.

Hiking (Mountain) Bicycle

In Fig. 2 is shown a bubble chart of Tensile strength versus Density for 67 materials as available in CES 4.5 Edu Level 2 [8] package. Consistent with an index of ½ for σ in equation (5), a straight line with a slope of 2 [derived as in equation (3) and (8)] is selected on this chart.

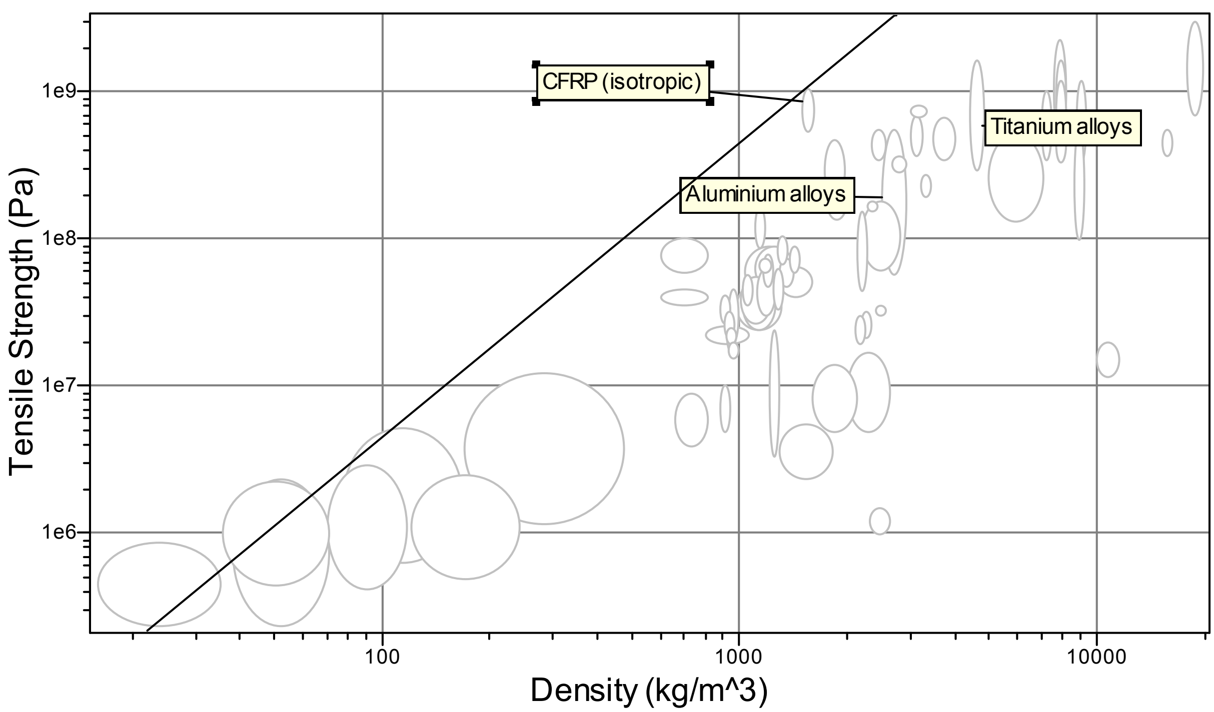

Fig. 2. Tensile Strength vs. Density Chart for Light, Strong Hollow Beam

The straight line shown passes through the top of the CFRP bubble and has a slope of 2 and an M_2 value of about 21.2. A straight line drawn parallel to this touches the top of both aluminum alloy and titanium alloy bubbles and has an M_2 value of about 8.9. It is therefore evident that for this design for a hiking bicycle fork, CFRP has the highest values of both M_1 and M_2 and is therefore the best-suited material. Aluminum alloy comes next as it scores over titanium alloy in the sense that its M_1 value is higher and has the same M_2 value as titanium alloy.

Cheap Transportation Bicycle

In Fig. 3 is shown a bubble chart of Tensile Strength versus Price per Unit Volume. Consistent with equation (7) a straight line with a slope of 2 [derived as in equation (3) and (8)] is chosen on this chart. The maximum values of M_3 determined from this chart are 8.0, 5.1, 0.35 and 0.24 for low alloy steel, aluminum alloy, CFRP and titanium alloy respectively. Since the objective is to make the bicycle fork with a strong, relatively cheap material, it is thus clear that low alloy steel is the best for this bike fork among the four materials, with CFRP and titanium alloy being far too expensive.

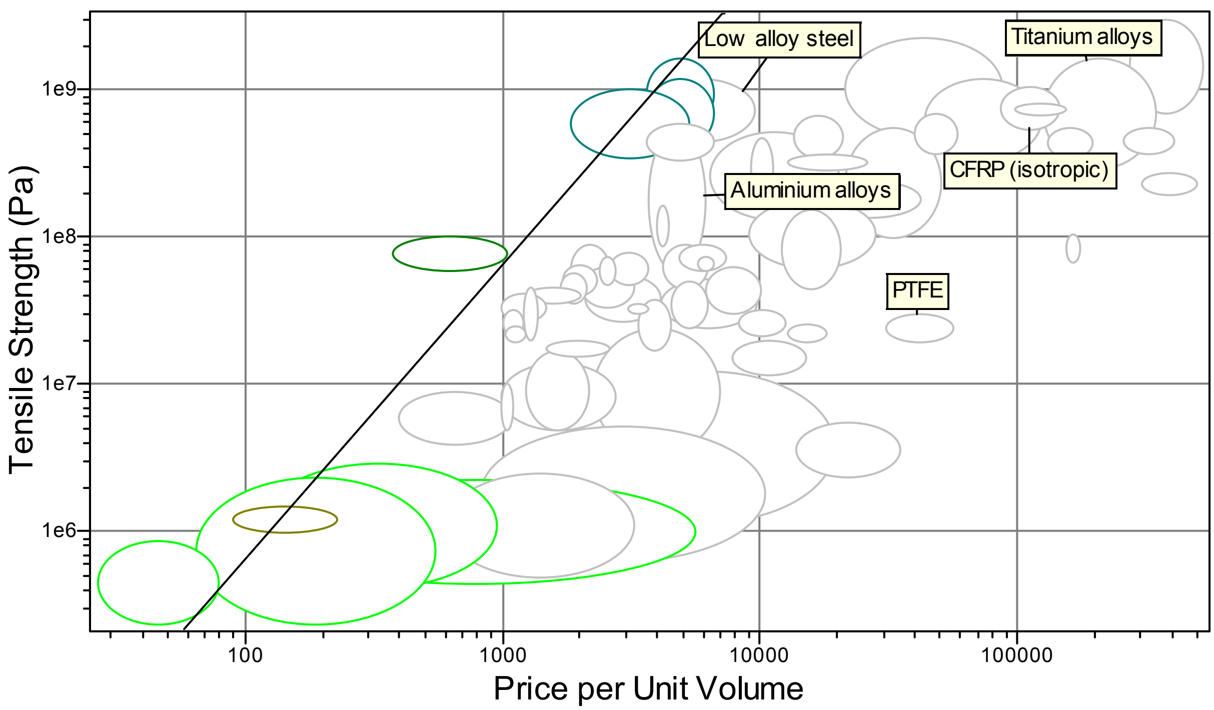

Fig. 3. Tensile Strength vs. Price per Unit Volume Chart for Cheap, Strong Hollow Tube

Process Selection
Once a material is selected for a given product, an appropriate manufacturing process will have to be selected for making the product. In general there are several alternate processes available for making the product using the chosen material. A good way of selecting the process is to consider the attributes of the different processes and the select the most suitable one based on the attributes and the product details such as the mass, quantity required and others as typically shown in Table-1.

In the present case, it is assumed that the forks are made from hollow tubes in all the materials considered. Using the "Tree" stage in CES 4.5 Edu Level 2 [8] for CFRP, 9 out of the 32 processes listed qualify. These are: autoclave molding, filament winding, lay-up methods, machining, pultrusion, resin transfer molding (RTM), vacuum and pressure bag molding, vacuum assisted RTM and waterjet cutting. Reference to bicycle frame literature indicates that there are three candidate processes suitable for hollow CFRP tube manufacture, viz., filament winding [8], lay-up method [8] and resin transfer molding [10]. The process descriptions and characteristics are made available by clicking on the respective process in the display window of CES 4.5 software. Some of these characteristics are compared in Table-1 shown below.

Table-1: Attributes of CFRP Manufacturing Processes

Process	Lay-up method	RTM	Filament winding
Mass range, kg	1 - 6000	0.5 - 50	0.01 - 3000
Section thickness, m	0.002 – 0.01	0.002 – 0.006	0.002 – 0.025
Economic batch size	1 – 500	1000 - 1000000	1 – 10000
Relative tooling cost	low	high	low
Relative equipment cost	low	medium	high
Labor Intensity	high	high	medium
Health hazard factor	high	low	medium

It is clear from Table -1 that each process has its merits and drawbacks. If only a small number of CFRP forks are required then RTM may be ruled out. If environmental and health considerations are primary then RTM would be best choice despite the break-even point being higher. The dependence on skill is less in filament winding than in lay-up method.

CES 4.5 software [8] may be used to analyze process information on the other materials in a similar manner. If more information needs to be generated then the guidelines given in Chapter 11 of Ashby's book [11] may be followed.

The principles and procedures outlined in this paper are equally applicable to other bicycle parts such pedal cranks, wheels and others. It should be noted however, that, the indices for Young's modulus and strength might change if the cross sections have different shapes. For example, Quaresemin, et al [10] have used a solid rectangular section for the CFRP crank studied by them and therefore the indices for Young's modulus and/or strength will have to be determined based on whether the width or the depth of the rectangle is kept constant [12]. For those interested in more information on bicycle science and design to be used for studies with CES 4.5 software, references [13], [14] and [15] are recommended.

Summary

This paper deals with a relatively new method for teaching mechanical engineering students about the selection of materials and processes using the powerful software CES 4.5. In this paper it is demonstrated that carbon fiber reinforced polymer is best suited for racing and hiking bicycle forks based on maximization of the material index. For cheap, transportation bicycle forks low alloy steel is best suited based on the same criterion. The ranking among several candidate materials for each application is also obtained based on the material index values. It is the author's sincere belief that the approach used in this paper will benefit a large number of educators and students, as has been intended by Ashby.

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Bibliographic Information

DR. MALUR SRINIVASAN earned his Ph.D. in Mechanical Engineering from the Indian Institute of Science in 1971. He has served as a faculty in the Department of Mechanical Engineering of Indian Institute of Science for 20 years and as a faculty in the Department of Mechanical Engineering of Texas A&M University, College Station for 10 years. He is currently Professor and Chair of the Department of Mechanical Engineering at Lamar University in Beaumont, where he has served on the faculty for 9 years. His teaching interest is in the area of materials and manufacturing.