TEACHING MECHANICAL ENGINEERING STUDENTS ABOUT MANUFACTURING PROCESS SELECTION USING ASHBY CHARTS

Malur N. Srinivasan

Department of Mechanical Engineering
Lamar University

Abstract

Mechanical engineers are often faced with the problem of choosing the best possible material and the best manufacturing process for a given designed product based on the constraints involved in making and using the product. Based on the geometry and the function of the designed products, the engineer should be aware of the alternative materials suitable for the product and the processes available for the manufacture the product using the different materials. For any candidate material, usually there are several alternative processes available for making the product and the best possible process for that combination of product and material. Needless to say, mechanical engineering students would be greatly benefited by being educated on these aspects.

In this paper an engineered product is chosen as the designed product and the suitable materials for the part are examined and the best possible material chosen using CES 4 software developed by Granta Design Limited. The software has extensive facilities for selection of the suitable materials based on the required properties of the part. The software also has facilities for choosing the processes interactively with the materials using charts developed by Ashby. Information on environmental, safety issues and cost can also be obtained from this software. Using all these data interactively the alternative processes for the combination of the part and the material are examined. This exercise gives the students an in-depth knowledge of manufacturing processes in the context of materials and designed products

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. In an earlier paper the present author has provided the details of the materials selection for bicycle frame forks using Ashby charts [3]. This paper is focused on process selection for the manufacture of forks using Ashby's method.

The bicycle frame fork was chosen as the principal designed product for several reasons. The primary reason is that the frame is a highly evolved mechanical structure [4] 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. 5]. 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 [6] developed by Ashby and his associates and licensed by Granta Design Limited 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, in association with the previous paper [3], will serve as a nucleus for developing formal courses on these lines to benefit mechanical engineering 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.
8. The number of forks to be manufactured depends on the purpose for which the bicycle is used.

Bicycles are used for different purposes such as cheap transportation, racing and hiking. The processes suited for the materials chosen in the earlier paper [3] for each type will be examined in this paper, as suggested in a course by Ashby [7].

Material Selection

As detailed in the previous paper [3], the best material for cheap, strong transportation bicycle fork is low alloy steel and carbon fiber reinforced polymer (CFRP) is the best material for racing and hiking bicycle forks. This paper therefore addresses the best process selection for manufacturing forks using these materials. For comparative purposes the process suitable for the manufacture of cheaper mild steel forks will also be examined. The Ashby chart used for selecting low alloy steel is shown as an example in Fig.1 [3]. In this figure, the tensile strength versus price per unit volume relationship for several materials is shown in the form of bubbles for each material. As explained in [3] the object is to find a material which has a high fracture toughness and which shows a maximum value of M (minimization of mass for a given strength) when a straight line with a slope of 2 is traversed along the chart. On the basis of both high M and high fracture toughness, low alloy steel qualifies.

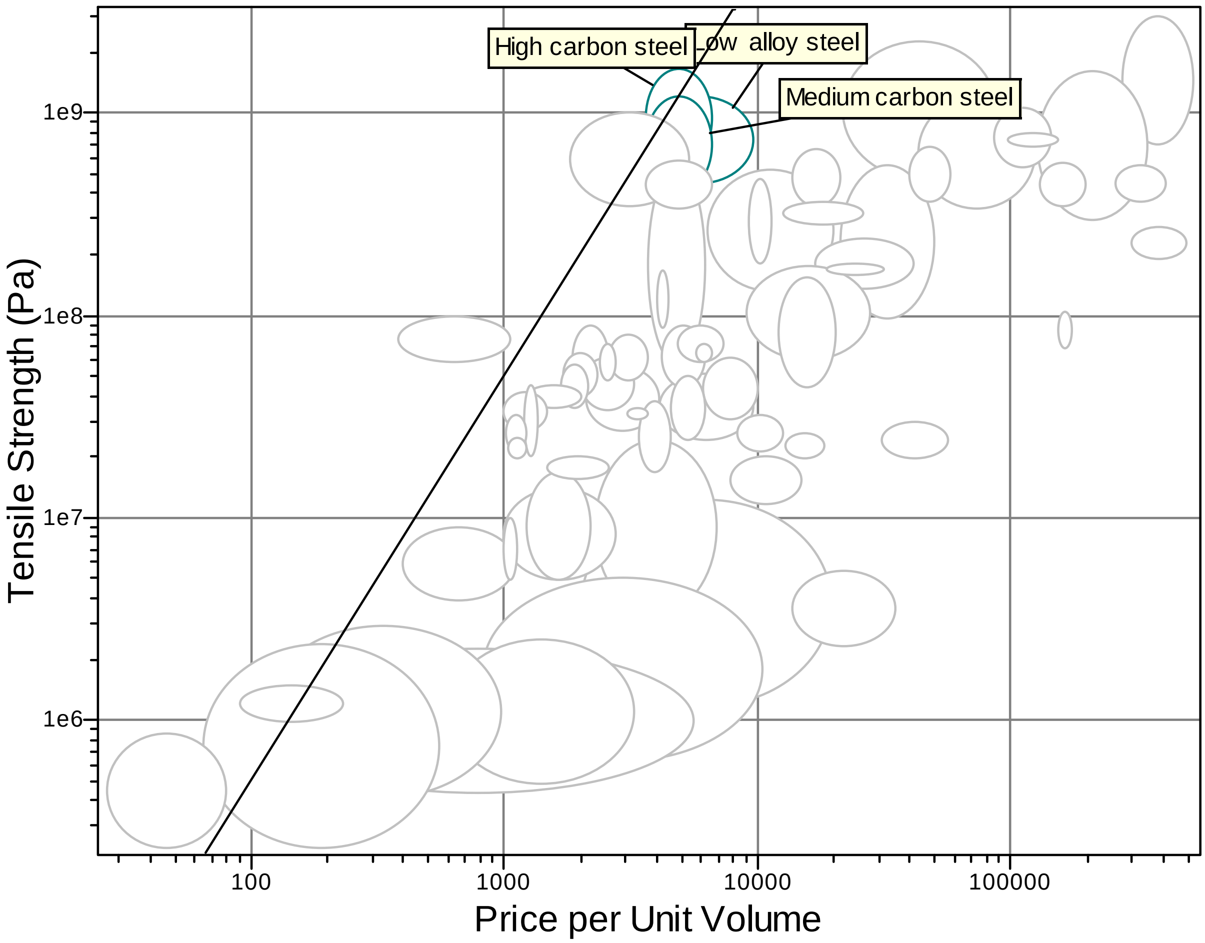

Fig. 1. Tensile Strength vs. Price per Unit Volume Chart for Cheap, Strong Hollow Tube

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 best process is to apply appropriate constraints in the "limit stage" of CES 4 and filtering out the non-suitable processes.

In the present case, it is assumed that the forks are made from hollow tubes in all the materials considered. The tube wall thickness is 3 mm, outer diameter is 4 cm, and length is 60 cm. In what follows, the step-by-step procedure to select the process (es) for CFRP bicycle frame fork will be described.

After activating CES 4, Edu Level 3 is chosen. The "select" button is clicked and from the process universe, "shaping" processes chosen. There are 121 shaping processes available in Edu Level 3. From the "tree stage" if composite shaping processes are chosen, there will be 12 processes displayed on left hand side of the screen. Now, the "limit stage" is chosen and constraints are applied as follows: Mass = 0.4 kg, Section thickness = 3 mm, Aspect ratio = 50, Quality factor = 5, Maximum batch size = 1000, Primary and Discrete process, Circular prismatic shape. When these limits are applied, four processes remain as candidates, namely filament winding, cold press molding, centrifugal molding and resin transfer molding.

Next the "graph" stage is chosen and the attribute "relative cost index" is plotted on the Y-axis, while "economic batch size" is plotted on the X-axis. The result is an Ashby chart shown in Fig. 2. It is seen that all the four processes qualify, on the basis of the applied limits, when the batch size is 1000. However, when the requirement is very low (say, 1-10), as in customized CFRP forks, only filament winding qualifies. At a batch size of 10, the relative cost index is in the range of 50,000 – 2,500,000 per unit using the filament winding process. The process record for filament winding indicates that it is well suited for making axisymmetric hollow parts.

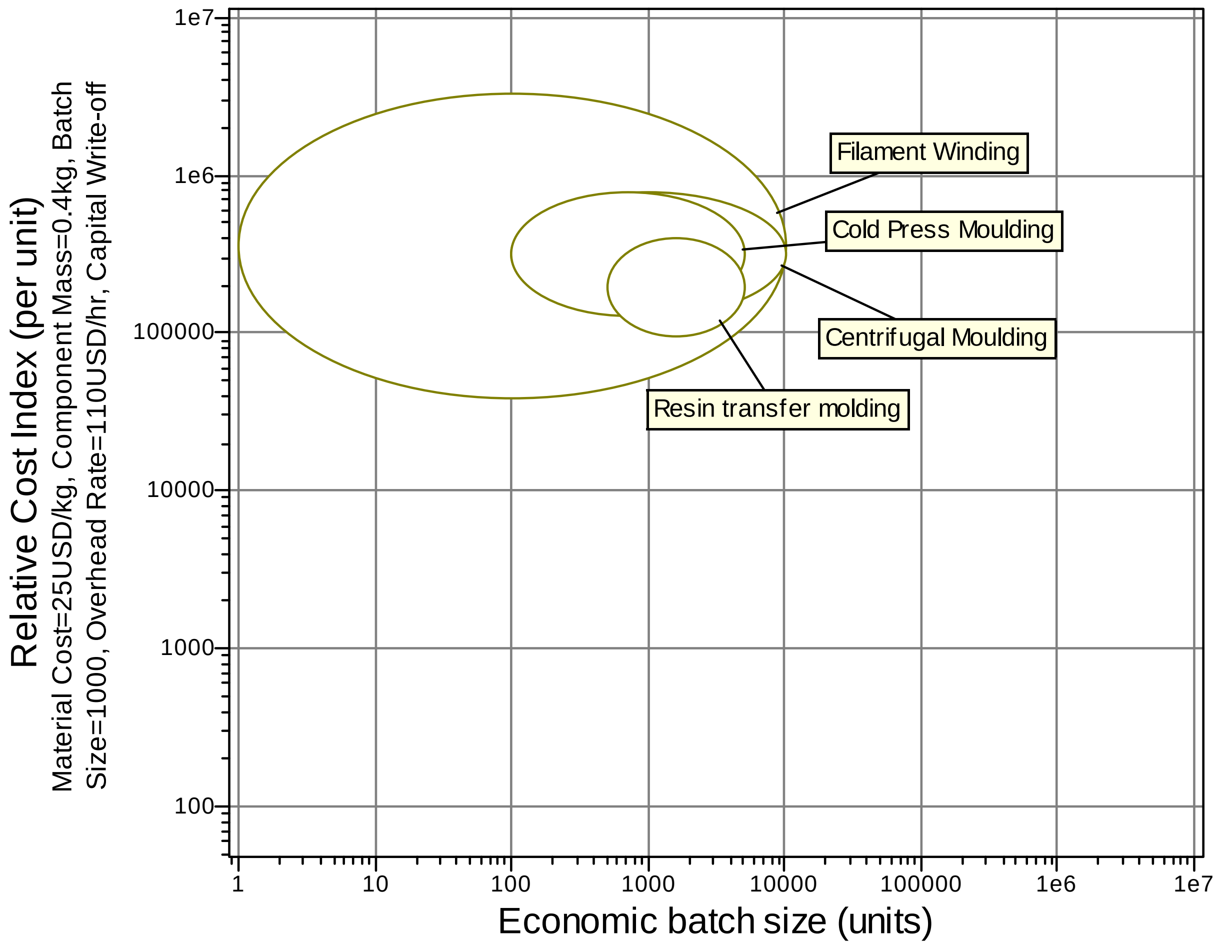

Fig. 2. Relative cost index vs. Economic batch size for filament winding, cold press molding, centrifugal molding and resin transfer molding

The process record for filament winding as available in CES 4 (after double clicking on "filament winding") is as follows [5]:

Filament Winding
General
Designation
Composite forming: filament winding
The process
In FILAMENT WINDING, axisymmetric parts are produced by winding the resin-impregnated reinforcement (rovings or tape) on a rotating mandrel. The winding pattern could be helical, hoop or polar depending on the application.
A multi-axis winding spindle could be used for winding more complex shapes. Winding is continued until the desired material thickness has been achieved.
The component is pulled off the mandrel as soon as it has hardened. The high reinforcement content of the process results in products with high strengths. The mandrel is made of either steel or plaster.

Process Schematic

Physical Attributes

Mass range	0.01	-	3000	kg
Section thickness	2e-3	-	0.025	m
Tolerance	* 1e-3	-	1.6e-3	m
Roughness	* 0.5	-	1.6	µm
Adjacent section ratio	1	-	3	
Aspect ratio	1	-	1000	
Minimum corner radius	3e-3			m
Quality factor (1-10)	1	-	9	

Economic Attributes

Economic batch size (mass)	10	-	2e4	kg
Economic batch size (units)	1	-	1e4	

Cost Modeling

Relative Cost Index (per unit)	4.059e4	-	3.301e6	

Parameters: Material Cost = 25USD/kg, Component Mass = 0.4kg, Batch Size = 10, Overhead Rate = 110USD/hr, Capital Write-off Time = 1.577e8s, Load Factor = 0.5

Capital cost	1.834e4	-	9.168e5	USD
Lead time	6.048e5	-	1.814e6	s
Material utilisation fraction	0.8	-	0.95	
Production rate (mass)	5.556e-4	-	0.01389	kg/s
Production rate (units)	3.333e-5	-	2.778e-3	/s
Tool life (mass)	200	-	2000	kg
Tool life (units)	100	-	1000	
Tooling cost	183.4	-	1.834e4	USD

Process Characteristics

Primary	True
Secondary	False
Tertiary	False
Prototyping	False
Discrete	True
Continuous	False

Shape

Circular Prismatic	True
Non-Circular Prismatic	True
Hollow 3-D	True

Supporting Information

Design guidelines

Axisymmetric hollow parts. External ribs, metal inserts and foam panels possible. No bosses and no undercuts allowed.

Technical notes

Common resin systems: liquid - polyester, epoxy; prepreg - epoxy; reinforcements: glass (60-80%), carbon, others - either in the form of rovings or tapes

Typical uses

Tanks, pipes, tubes, pressure vessels, drive shafts, wind turbine blades, rocket noses, etc.

The environment

The process usually requires low viscosity resins, which are more hazardous than other, thicker, resins.

Links

Reference

Shape

Structural Sections
Material Universe

Comparison of the process record of filament winding with the other three processes suggests that it is the best-suited process for making parts such as forks.

The students can gain invaluable knowledge on filament winding from this concise, yet comprehensive record.

The processes suitable for making bicycle forks from low alloy steel (strong and relatively cheap) and mild steel (very cheap) are chosen in a similar manner. In Fig. 3 is shown the Relative cost index versus Economic batch size for the alternative processes indicated by Ashby process, namely the swaging process and the cold heading and upsetting process. If a batch size of 10,000 is chosen, it is evident that only the swaging process qualifies. Examination of process records of these two processes indicates that swaging is better suited for making hollow cylindrical tubes than the cold heading and upsetting process.

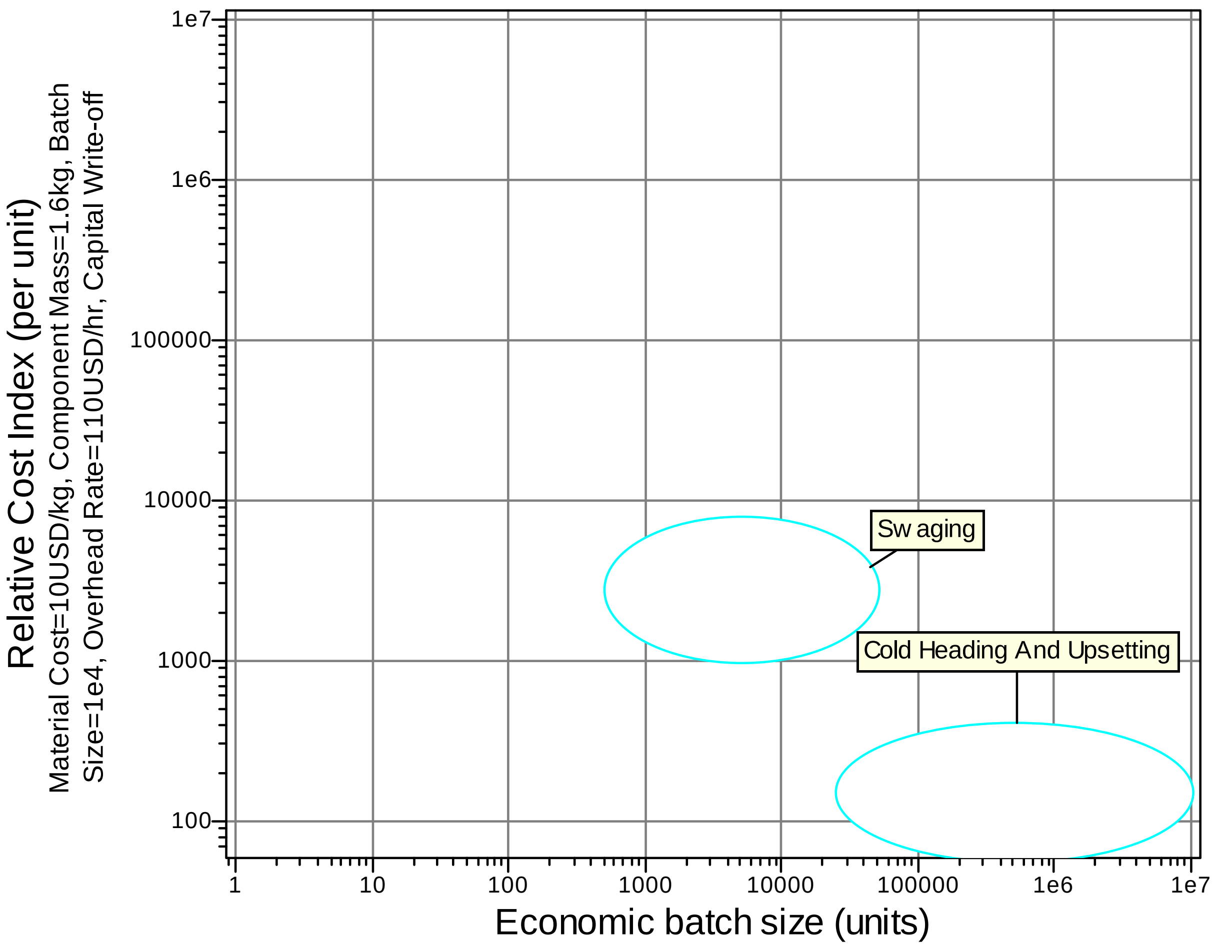

Fig. 3. Relative cost index vs. Economic batch size for Swaging and Cold Heading and Upsetting

In Fig. 4 are shown plots of Shear Strength versus Production Rate for projection welding and seam welding that qualify for making mild steel forks. Examination of the process records for these two processes indicates that seam welding is better suited for the forks.

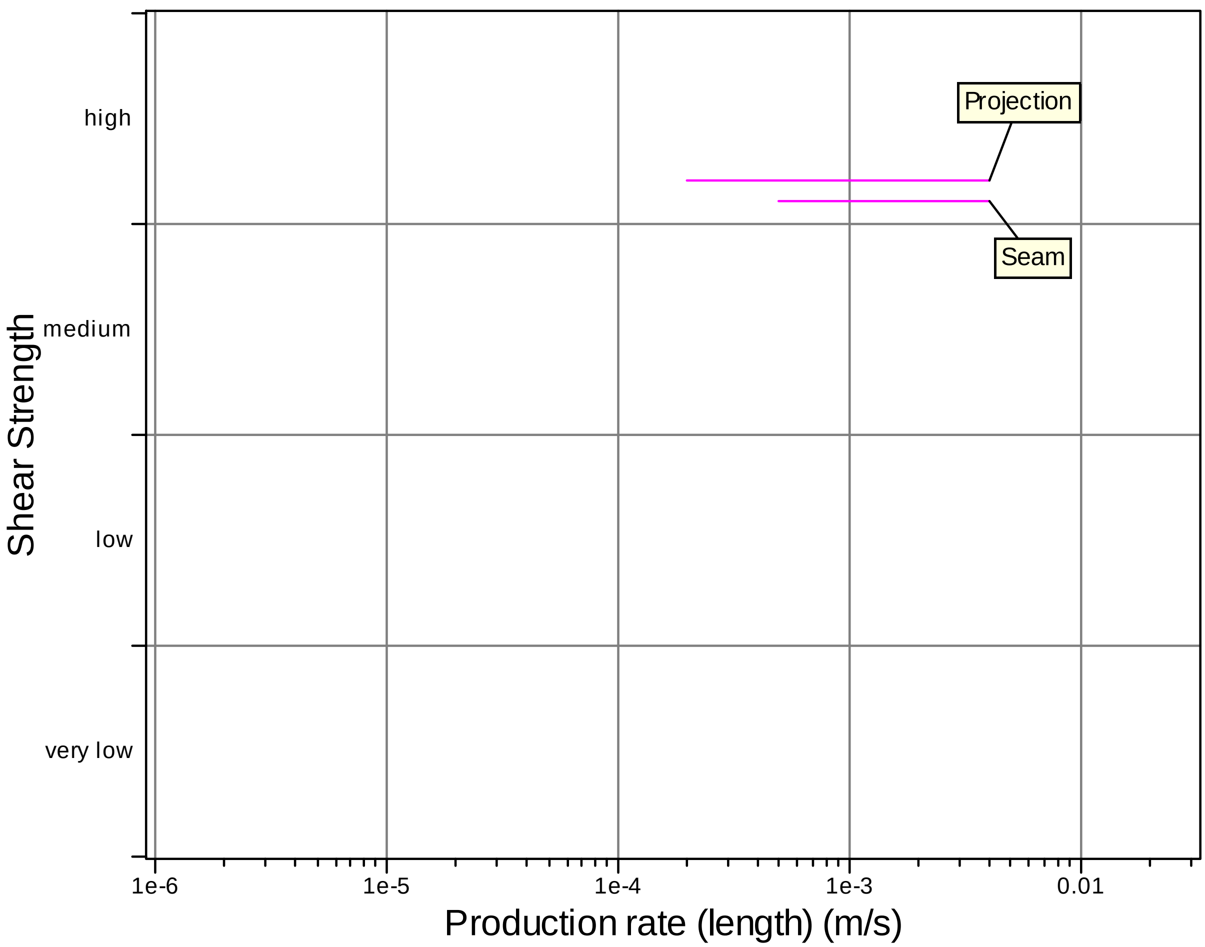

Fig. 4. Shear strength and production rate for different joining processes

Summary

This paper deals with a relatively new method for teaching mechanical engineering students about the selection of manufacturing processes using the powerful software CES 4.5. In this paper it is demonstrated that filament winding is best suited for racing and hiking bicycle forks based on the limits applicable, particularly the small number to be manufactured. For relatively cheap, transportation bicycle forks made of low alloy steel, swaging is best suited based on the applicable limits, particularly the number of forks to be made and the process record. For very cheap transportation bicycle forks, made of mild steel sheet, seam welding is the best-suited process. 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.

References

1. M.F. Ashby, Materials Selection in Mechanical Design, Butterworth-Heineman, Oxford, 2nd edition, 1999, 1
2. ibid., 1-502
3. M.N. Srinivasan, " Teaching Materials and Process Selection to Mechanical Engineering Students", Proceedings of the 2005 Annual Conference of American Society for Engineering Education, Portland, Oregon, June 2005.
4. S. Nicol, "Metallurgy for Cyclists, The Basics", http://www2.sjsu.edu/orgs/asmtms/artcle/articl.htm
5. http://www.google.com
6. CES 4.5 Software, Granta Design Ltd., Cambridge, 2004, http://www.grantadesign.com
7. M.F. Ashby, "New Approaches in Materials and Manufacturing Education", June 20, 2004, Salt Lake City, Granta Design Limited.

MALUR N. SRINIVASAN

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 10 years. His teaching interest is in the area of materials and manufacturing. He is a registered professional engineer in the State of Texas.