TRANSPARENT STEEL:

the teaching of creative design

by Harry Bhadeshia*

It is often creative design that leads to significant wealth creation. How can it be incorporated into materials science courses?

The teaching of design in materials science generally takes the form of Galileo's square–cube law. The weight of a structure increases with the cube of its dimensions, but the area of the load bearing sections increases only with the square of the dimensions. Consequently, an elementary structure which is scaled upwards may eventually fail under its own weight.

Modern versions of this kind of teaching involve the quantitative analysis of measurable material variables such as yield strength σ_Y and Young's modulus E. Therefore, the best material to design a leaf spring to tolerate a given deflection without yielding would be one which has the highest ratio of σ_Y/E. Such thinking is routinely expected of any trained materials scientist. This statement, nevertheless, requires some qualification.

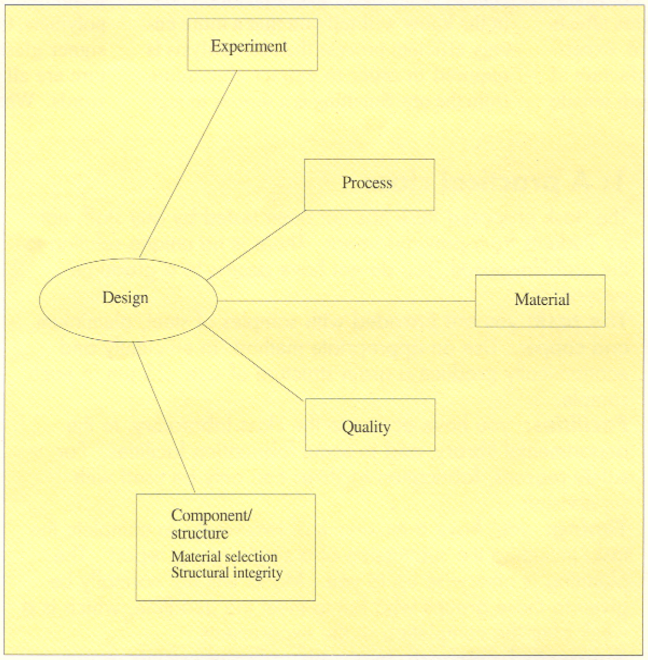

Figure 1 Design in the context of materials science

A materials scientist must understand the methodology behind the derivation of these square-cube type laws. In elementary cases, knowledge of the actual equations may even be required. However, in most cases, it is likely that the scientist can consult an engineer for help with the quantitative rule, or may be able to access computer programs for such calculations. It is easy to imagine some menu driven materials selection program with facilities for yield, deflection, weight etc, controlled design and even combinations of design criteria.

There are many cases in science and in enterprise, where it is not technological design, but creative design which leads to significant wealth creation. A perfect example is the Sony *Walkman*. It is not the technology of the tape recorder which led to an immense increase in its sales, but rather an artful manipulation of format.

There have been a number of detailed studies and recommendations about the teaching and practice of design in the engineering profession. The general principles are therefore well researched. Creative design nevertheless remains extremely difficult to teach, primarily because the principles are abstract whereas applications develop more rapidly from examples.

Most of the design exercises in materials science tend to focus on materials selection, which is a means to an end, ie a tool, more than something which leads to an invigorating outcome. Woody Flowers of the Massachusetts Institute of Technology has developed methods which have been proven to inspire engineering undergraduates, so much so, that his scheme has now been internationally applied. This article contains suggestions for adapting some of his ideas for materials science.

It is stated in learned reports that elements of design should link all of the engineering courses that are taught at a degree level. Engineering courses are, however, significantly different from materials science courses in terms of goals and the nature of the students that they attract. Most of the research on design has focused on the engineering subject, sometimes with derisory comments about materials science and in general about the role of science in engineering. It is necessary therefore to have a look at design from the point of view of materials science, which is after all more interdisciplinary than engineering or the more common natural sciences. This could be a major advantage as far as design is concerned; in particular, a well trained materials scientist should be able to communicate effectively with technologists and scientists alike.

Figure 1 summarises some of the obvious aspects of materials science in which an element of creative design may be useful. We may often be called upon to design experiments either to rank new materials or to develop them. The current trend in the highly competitive aircraft industry is to reduce the time taken from the point where a new engine or airframe is conceived to its manufacture and certification. Well designed experiments are

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Table 1: Possible routes for teaching design in materials science

Conventional	Unconventional
Practical	Inter-departmental project
Example classes	Inter-university project
Literature survey	Market research
Case study	Industrially organised brainstorming
Research project	Student originated research project
Industrially based project	Involvement in real industrial design
Investigation of artifact	Real failure investigation
Computer-aided design	Software design
Selection exercise	Role play

therefore necessary to ensure that materials, which can make or break particular manufacturers, do not form the rate limiting stage. It is rare indeed to find an undergraduate materials course in which the design of an experiment is the core of a practical class; the normal way is for students to perform tried and tested scripts.

It is not difficult to distinguish between a well crafted experiment and one which is based on brute force. For example, in cases where a tensile stress affects transformation, most reported experiments have involved the manufacture of a series of parallel gauge length tensile specimens. These are then tested at different loads, so that the resulting microstructure can be correlated against a number of discrete values of applied stress. On the other hand, a single tensile specimen with a slightly tapered gauge length could be pulled to failure. Continuous information is thus obtained, from a single test, of the influence of stress on microstructure. It is probable that materials scientists are more involved in the design of experiments than their engineering colleagues.

Materials scientists often play a key role in the making of new manufacturing processes, usually as a part of a team. The subject is already taught widely in a variety of guises – for example, most materials undergraduates at some stage do a comparative study of ingot and continuous casting. Case studies like these are important, but on their own, probably not sufficient to inspire thinking in all but the best of students. For that it is necessary to present an unsolved problem. For example, any realist would argue that there are many outstanding and serious problems with the use of aluminium in the mass production of car bodies. Price, of course, is one of the major factors. Those in the know will tell you that a more energy efficient process than electrolysis is required in order to extract aluminium from the ore. Smelting is a serious though unestablished alternative; it would be educational and interesting to consider the design of such a process, taking into account thermodynamic, economical and capital cost factors. Such an exercise would also involve a survey of existing literature.

The design of materials *per se* is probably already a major component of current degree courses – alloy design (using quantum mechanical to microstructural techniques), the molecular design of polymers, the fabrication of ceramics, designer glasses and composite manufacture are all familiar and important buzz words. What appears to be lacking however, is an ability to analyse what could be done once a new material is invented. For example, successful research in the steel industry led to the manufacture of what could be a revolutionary steel for rail applications. Whereas the academic partner of this work was satisfied with the success, the industrial partner had the vision to institute a series of studies involving wear resistant materials in a number of applications which have nothing to do with railways.

It is difficult to see how students could be involved in a good, exciting exercise on the design of a novel structure or component. In industry, projects like these are carried out by large teams consisting of many disciplines. For example, to design a novel geometry for steel beams of the type used in the construction of multistorey buildings, requires wide ranging expertise. Structural engineers are able to analyse for stability to buckling under a variety of complex loads, and to advise on safety factors. The knowledge of fire engineers is necessary in order to ensure, as the standards require, that the building does not collapse within a specified period of time,

1: A practical class

The task proposed here has not been tested by any staff, nor by students from previous years. There is no unique solution to the problem posed. You do not have access to a graduate supervisor.

The task: you are provided with samples of steel, aluminium and copper. Use an appropriate method to efficiently and economically produce a grain structure of size 25 µm in each sample.

Facilities: you have access to the class laboratory, to the departmental library, and to some fabrication facilities. For safety reasons, fabrication facilities can only be used with supervision.

Timing: you have a maximum of two weeks to complete the task, including the submission of a single group report. The planning is otherwise up to you. Marks will not normally be given to those groups who fail to meet the deadline, which is a week after the completion of the experiments.

Suggested method: begin with a brainstorming session within your own group. This means a free floating and listing of ideas, without worrying about the soundness or practicality in the first instance. Formulate a reasoned plan on paper. You can then consult a member of the academic staff. Each such consultant will only deal with one group, and will discuss the matter for no more than 30 minutes. The academic consultant will also ensure the safety of whatever you propose to do.

Implementation: implement the plan at will, making appropriate adjustments as necessary.

Report: produce a group report which should include: proof of success ■ cost analysis of the optimum methods proposed ■ science in sufficient detail to enable a reproduction of your work.

Assessment: the project will carry the usual mark for a single practical and all undergraduate members of a team will receive the same mark. Each member of the most successful team (including the academic consultant) will be rewarded with a 'materials designer' T-shirt. Note that it is in your interests to avoid discussing your work with any other team.

due to a loss of strength in the steel as it is heated by the fire. Rolling technologists have to make the actual sections from standard ingot shapes – they may insist that their machines cannot cope with odd shapes without large scale capital investment. Finite element modellers may predict whether it is possible even in principle to roll certain shapes while at the same time ensuring uniform properties. Metallurgists are required both to test any new sections and to develop steels designed to transform to uniform microstructures on cooling, in spite of non-uniform deformations encountered during rolling. Accountants are essential to cost the research, to trek the costs during the project, and to indicate the level of beneficial change necessary before it becomes viable to invest in a new manufacturing process. Market research plays a key role in such a venture.

2: Examples class

1. A new material recently discovered is steel which is transparent, but which otherwise has all the properties of a normal steel. Find applications capable of exploiting this material, in the manufacture of: an item suitable for popular consumption ■ an expensive item which could be regarded as a work of art ■ an expensive item which has tangible use ■ an item which cannot otherwise be made.

2. Buckminsterfullerenes are large carbon molecules with interesting topology. They can be in the form of, for example, footballs, tubes or baskets. Describe ways in which this kind of carbon might be exploited in the fields of: tribology ■ catalysis ■ alloying ■ basic research.

3. A new device allows the high resolution (≅ 10 nm) measurement of elastic modulus. Discuss potential applications in materials technology and science.

4. What are the chances of commercial success for each of the following products: perfume costing £2 per bottle ■ breakfast cola ■ a neck-tie with a pocket for credit cards ■ a credit card sized torch costing £4.

5. What could you invent with the knowledge that a transparent polymer strip clouds when overstretched?

6. What are the costs of filing and defending a patent? What are the alternatives to patenting an invention?

7. Are the following items subject to patent protection? The sound that a car door makes when it is closed ■ nickel–base superalloys ■ a mathematical formula which predicts whether an alloy should exhibit reversible (shape memory) martensitic transformation.

8. A solid-state phase transformation is induced by the application of a stress at ambient temperature. What is the most economical experiment you could design to: measure the fraction of transformation as a function of the magnitude of tensile stress, the maximum value of which should be the ultimate tensile strength of the alloy ■ measure the fraction of transformation as a function of the shear stress, the maximum value of which is kept below the shear yield strength?

Most degree courses do not have the resources, especially in terms of time, to support such an approach. The practical suggested earlier is in this sense a feeble attempt. Role play on the scale of an entire class may be an approach worth trying.

Many undergraduate courses involve the study of artifacts in the form of a manufactured article. The students are required to disassemble a component, examine the materials using a variety of techniques, and then make some recommendations on how the component might be manufactured better. The difficulty with such exercises is that the subject of materials science is now so broad, that there is a distinct lack of depth in what is taught. Students are therefore not sufficiently capable of systematically investigating the complex industrial materials present in commercial components. Because such components are usually well manufactured and designed (otherwise they probably would not be available) there is little, within the scope of their knowledge, that students can do to suggest realistic improvements. Artifact based projects have therefore become less interesting to students.

Some ways in which creative design is, or may be incorporated in the materials science degree curriculum are presented in Table1. Both conventional and unconventional approaches can be pepped up using the rules described earlier. It should be obvious that the task is not simple, and that time and other resources would have to be diverted from other aspects of teaching and learning. But the subject is certainly useful, challenging and worthy of further discussion.

The features which make the teaching of design distinctive can be summarised as follows:

◆ The act of bringing ideas into being is exciting; a task must therefore be set which is genuinely perceived to be new. This also means that the task must be different for each year that the course runs.

◆ There should be no unique answers to the design problem. It otherwise reduces the problem to the more barren scientific design.

◆ The task should be stated with brevity. The aim is not to lead the students but to allow the ideas to originate freely.

◆ There must be a considerable element of education hidden in the form of fun.

◆ Issues of safety may require some supervision. There is an educational element in this. The student may be required to carry out Control of Substances Hazardous to Health (COSHH) assessments of any chemicals used. This is not a part of the normal undergraduate curriculum.

These rules and the general concepts propounded by Woody Flowers are illustrated with two specific cases for materials science. The first is a practical class which is attempted by students in teams of three or four, box 1. The second is an examples class in which students can work in small groups or as individuals, box 2. These cases are stated in a form suitable for presentation to students.

The practical class in particular encourages team effort. The group has to produce a single report, with each member of the team getting the same mark after assessment. It also mirrors the sort of situation which might arise in industry, where a market manager sets a task and a deadline without giving expert guidance. As in industry, there is limited access to a consultant. Efficiency and cost are important considerations which are also featured.

Further reading

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