The modern place of materials science and engineering

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Abstract

The reasons for the recognised importance of materials science and engineering in the development of a modern economy are outlined and it is explained why this is accompanied by a more efficient use of materials. © 1999 Elsevier Science S.A. All rights reserved.

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1. Introduction

During Herbert Herman’s distinguished tenure of the editorship of Materials Science and Engineering-followed by his editorship of Materials Science and Engineering A which commenced in 1988 and since then his role as Chairman of the Advisory Board of both A and B journals our subject has developed mightily.

When I received an invitation to contribute to the special issue to be dedicated to Professor Herman’s sixty-fifth birthday I was led to speculate on why it is that our subject is now of such recognised importance. We appreciate that it has always been important, but the recognition of this by our colleagues in other engineering and scientific disciplines is, I believe, a recent phenomenon. In the following short contribution I adduce some reasons why. I start with a paradox.

In all developed countries of the world the material contribution to wealth creation decreases as the wealth of the nation (or region) increases. This can be demonstrated in a number of ways. One way, which I like, is to plot the wealth per person (gdp/capita) measured in units of say $ per head per year as a function of time — say year by year — on a graph, and to compare this with the amount/material used per person — say steel measured in kilograms consumed per person per year.

One finds that as the income per person increases the amount of steel consumed per person either remains constant over the years or more usually goes down. What is true for steel is true for all engineering materials from steel through tin to rubber, to plastics, and, this may surprise you, to silicon boules from which most computer chips are made. Some data are presented in Fig. 1.

Does this mean that modern economies are based more on providing services than on providing food, fuel and manufactured objects? Such could be part of the answer for the difference in slope of the curve representing increase in wealth with time compared with that representing consumption of engineering material. It does not account for why consumption of steel, of nylon, or of cement, all measured per head of the population, should actually decrease with time.

2. Scale of primary production

Now, the decrease with time is no doubt mainly due to the cleverness, skill and ingenuity of the engineers concerned with the production of engineering materials and with their successful fabrication into useful artifacts and the distribution of these to the consumers.

The efficient primary production of engineering materials depends on scale and large scale production when appropriate, e.g. for steel, glass or polyethylene, leads to the efficient use of energy, great reduction in waste, the partial elimination of scrap and the produc-
tion of a clean well characterised product. This product is often of the shape or form necessary for subsequent operations also to be carried out without waste and subsequent loss due to, say, the need to machine or cut to shape, etc. The advances in these areas over the last few decades are such that it is possible to claim that so far as size of the primary production unit is concerned the optimum size has been reached for say a blast furnace or an ethylene cracker, or a cement kiln and perhaps for a silicon boule.

The efficiency of primary production and, for many important commodities, its restriction to a small number of geographical sites, on a world wide basis, is only again a small if very important part of the story.

3. Optimisation of material

Another part is due to our understanding of the need to obtain more nearly optimum physical and chemical properties of the solid materials of which all manufactured (or for that matter ‘naturally’ produced) objects are made. This has come about by understanding the properties of defects in solid materials so that materials can be made, for example, stronger, hence less is required to bear a given load, or more electrically conducting so less is required to carry a given electric current, or a better sound absorber is produced so less is required to provide a quiet environment.

The chemical composition of the material will be adjusted to bring about the optimisation of these physical properties relevant to a given function. The chemical properties will also determine whether a material is oxidised in air and hence its properties degraded, or whether it is corroded by, say, fruit juice. The material therefore retains its properties in service or if subject to adverse environmental conditions and is made more resistant to wear. All of these improvements mean, of course, that a material lasts longer and hence does not need to be replaced so frequently. This means that the amount of primary material which had to be produced to meet a given function decreases as our engineering skills, our chemical skills, our physics of materials become better and better; which is what usually happens in an advanced or developed country or region.

It is also noteworthy that we understand how to join materials together very well, not only copper to stainless steel, say, but materials with quite different properties, ceramic fused to metal, plastic coated steel, plastic bonded to leather, and a thin film of tenacious plastic covering the warp and weft of a high performance racing sail. So almost no material is used alone, it is usually a composite materials of some form or another.

4. Other disciplines

If what I am saying is a true reflection of what is happening then one might expect that in developed
societies materials science and engineering might be in less demand than before, because, after all, with the plethora of successes behind us why should new material sciences and engineering be needed at all?

In fact the opposite is happening. In professional engineering circles at present, among those funding research in government and in industry, among professional engineers there is a quite unprecedented interest in materials engineering. Whether in heavy industry, making ships, whether making aircraft, or whether making television sets, there is great interest. This interest is not solely concerned with ‘new’ materials, i.e. those new to the world. It is found among those interested in steel and other constructional materials, but also among those interested in functional materials, silicon chips, laser materials, piezoelectrics and photochromics. It is interesting to see what is going on in the professional societies and in the Universities. The electrical engineers, the mechanical engineers and the information technologists are all forming groups to consider materials. Twenty, or even 10 years ago this was left to the material societies, more usually the metallurgical societies or the rubber and plastics groups. In the Physics and Chemistry Departments of the major Universities there are very important programmes and large budgeting disbursement on subjects indistinguishable from those found in Materials Departments. The funding agencies are spending large portions of their budget on materials, though often disguised under various other headings.

Why is this? Again, there are several reasons. One obvious one is concern with the environment. All environmental problems have a material base, and there is general public awareness of the need to do more with less. But this is not a hard and urgent driver for many people.

5. Effect of technological stalemate

One very important, perhaps overriding, reason is that with an important exception which I outline below most modern technologies, in fact all of the major ones concerned with energy production, the provision of food, the means of personal and cargo transportation and with the provision of shelter, are all now mature technologies. At the beginning of the century we had trains, cars, aeroplanes, electric power stations and the mechanisation of production had begun. The producers of these artifacts, aero-engine makers, car makers and construction companies, compete world wide. The major exceptions are the introduction of nuclear energy and the revolution in information processing via the computer — made possible by solid state electronics.

Under the conditions of what has been called technological stalemate in the major manufacturing industries the importance of materials for improvement of performance becomes paramount. Using less material, processing it faster, making it last longer, making it stiffer, lighter — so easy to move, and stronger.

Due to the labour of the materials scientist in improving properties new materials have been synthesised, some new to the world, e.g. Bucky balls, but more important right now, newer materials or materials new to a particular use, e.g. plastics in car bodies and in our own bodies, conducting glasses and ceramics instead of metals as bearings and gaskets. As important is the discovery of the composite principle which enables combinations of properties not available in a single material and the subset of this, surface engineering, cladding and coating and ion implanting, etc.

Now, of course, all manufacturing is materials processing and the longer that takes the more expensive the end product, so manufacturers want to form materials to shape more quickly than before. To do this they must understand the material and find new and faster methods of forming it, e.g. superplasticity in a ceramic.

What has been called materials processing meant getting the material ready for the material supplier to provide to a customer; so selling bar stock or rolled steels or plastic granules or bottles of adhesive fluids or a paint, or an ingot. Now however, it is becoming very different. Material properties and processing pervade the whole manufacturing process, materials must be combined in the final product, not just machined or extruded to shape, though these remain important procedures.

Furthermore, in order to prolong the life of a material under severe service conditions its behaviour should be monitored. To reduce waste during fabrication the properties of the material during processing to the final artifact should also be controlled so that deviations from the ideal processing schedule are minimised. To see how this is done we must return to the revolution in information processing made possible by the computer. The development of the computer depends critically on the introduction of active surfaces. The active surface of a silicon chip is only a few microns thick and contains the device, e.g. the field effect transistor, which is the heart of the machine. Such active surfaces and ones like them made from functional materials or devices, e.g. piezo electric or a capacitative junction or a small pair of electrodes as in an electrolytic cell, may be used to detect affects within a material such as temperature, pressure, activity of a particular chemical species and other important parameters for the manufacture of a material. So, if such sensors are immersed in a material when it is being made or when it is in service its internal constitution can be monitored.
6. Process modelling

But this monitoring either of the life of a material during service, or in the process of manufacturing it, is not the only, or at present not the most important, aspect of how the computer affects materials engineering. This second and perhaps the most important method is through ‘process modelling’. This can lead to:

- Reduced development lead times of a new material.
- Reduced development costs.
- Improvement in product integrity and reliability.
- Improved design tools and manufacturing capability.
- Improved materials utilisation.

These advantages occur through an accurate process modelling operation. A process model is essentially a computer-based numerical simulation of a manufacturing process based on its fundamental physics. The behaviour of the material must be understood through its volume and what are called finite element models of material behaviour are used to accomplish this. These tools allow us to mimic, magnify and simulate reality and they allow us to test the process in a computer.

For instance, if a simple casting operation is to be carried out then such things as the rate at which the cooling proceeds depends on the geometry of the support; if a material such as the silicon boule we referred to earlier is to be withdrawn from a furnace then we know the withdrawal rate. This leads to reduction in scrap rates and an increase in effective foundry capacity, a reduction in material usage and fast new part introduction.

Another reason why process modelling is so important is that with the plethora of new materials available it is not economically possible to carry out experiments on each one to test whether they are applicable in a certain area of engineering or for a particular artifact. We must often rely on a modelling process to find out whether they will be be.

7. Design

Because of the prime place for materials in all industrial sectors a change of the role of the materials engineer is becoming quite apparent. It has been said by a prominent politician recently that despite the importance of materials the selection and design are factors that are taken for granted or poorly understood. True, and the recognition that a material is to be designed is so important. But selection and design must become one and it is this unity that the materials scientist/engineer must make his own.

Recently the process of selection of a material by property has become much more systematized using the computer and we are beginning to use the computer via modelling procedures to select the appropriate process of fabrication, but design is still seen as an analytical procedure. It should not be in my opinion. It is synthetic and artistic and requires imagination and inspirational flare as well a mastery of the effect of property on performance. Only the materials engineer who combines tactile experience of the many materials offered, the soft plastics, the brittle rare earth magnet, the shape change accompanying a transformation of crystal structure with a knowledge of the properties produced, will accomplish this most effectively.

I recently asked an extremely eminent materials scientist/engineer with a world wide reputation what aspect of materials he was currently engaged upon. He replied “I am not in materials, I am in design”. Unwittingly, he had stated exactly where the centre of growth of the materials field is, no doubt due to his efforts and those of many like him.

I fear, however, that by design he still meant analysis of the properties needed. I wish he had said synthesis — which usually means just chemical synthesis. Important though this is I mean something much more. I mean synthesis of an artifact to carry out a specific function embodying choice of the nuclear properties (where need be), the chemical properties of the constituents and their combination into the artifact with a synthesised structure, microstructure or mesophase, or whatever. It is mastery of the control of what I call microstructure that is the province of the materials scientist and is inherent in the design of a material artifact. The computer is what makes this possible, coupled with models of how material behaves when irradiated, beaten, drawn or worn. Getting that right and getting it right first time is what modern materials science/engineering is about. The countries, regions or economic groupings that understand this and train and lead their materials specialists to do it will be the ones who maintain manufacturing capability in the highly competitive world of the 21st century.

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