Aims and objectives of a degree in Materials Science

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1. Introduction

In this paper I focus on the aims and objectives of a degree in materials science as opposed to any other subject. The general educational aims and the professional skills I mentioned in the previous paper will not be discussed any further here. Our attention will be directed to the academic aims and objectives of a degree in materials science, as distinct from a course on physics or chemistry or engineering.

While thinking through this paper it soon became apparent that I had to address the questions ‘what is materials science’, and indeed ‘what is a material’. There were some surprises (for me anyway) in what emerged from this difficult process.

2. What is Materials Science?

It is not easy to give an all-encompassing definition of materials science because the subject is so broad and inter-disciplinary. Graduates who entered materials science in the past often came from physics, chemistry, engineering, earth sciences and mathematics. With the growth of biomaterials medics, biologists, biochemists and biophysicists have joined in, and a whole issue of *MRS Bulletin* was recently devoted to the ‘Materials science of the cell’. Whatever definition we offer it has to reflect the richness and diversity of all this activity. But perhaps we should first define a material, so that we can then think about the science that is applied to materials.

2.1 What is a material?

The OED definition of a material is *The matter from which an article, fabric or structure is made*. This is a good starting point. One usually thinks of articles, fabrics and structures as being solid rather than liquid or gaseous objects. But liquids are an important part of materials science, for instance in melt processing, which includes investigations into mass and heat transport in liquid metals during casting, and in liquid phase sintering of ceramics, sol-gel processing, and the properties of liquid polymers for injection moulding and spin coating. In all these examples the liquid is a means to an end, which is the production of something solid. In such cases, we tend not to think of liquids as materials, but they are used to create them. However, biological materials are often in a liquid state, e.g. liquid-phase lipid bilayers which provide the structural basis for the membrane that surrounds every living cell. Water plays a crucial role in many biological processes such as protein folding. Liquids undoubtedly qualify as materials in biological processes. Liquid crystals are further examples of materials that are not solid. Colloids, which are dispersions of small solid or liquid particles in a liquid or gaseous medium, include emulsions, foams and sols. They are all important materials. For example, another issue of *MRS Bulletin* was recently devoted to the ‘Materials science of food’, and the production of food must be one of the largest materials industries world-wide!

If liquids must be included in the definition of a material, what about gases? Gases are often used to grow electronic materials by a variety of vapour deposition methods.

Industrially important ceramic powders are often created in aerosol reactors from gases. Gases such as helium can become trapped in nuclear reactor materials and form bubbles, which contribute to the hardening and embrittlement of the material. In all these cases gases are used either to create solid objects, or they affect the properties of a solid object. However, we do not think of the gas as a material in itself. But what about small isolated clusters of atoms such as C_{60}, or small isolated metallic clusters produced by atomisation of streams of liquid metal? The study of the structure of these clusters has led to the discoveries of carbon nanotubes and 'magic numbers' in the frequency of occurrence of metallic clusters as a function of their size. Surely, such cases show that even gaseous matter can usefully be studied by materials scientists. Materials scientists have analysed the particles in various smokes, which has led to a means of characterising and distinguishing different sources of smoke pollution.

If solid, liquid and gaseous matter are all within the remit of a materials scientist what makes a material *a material*? For instance, why don't we naturally think of naturally occurring gases, such as air, as materials? I think the answer is that some form of matter becomes a material when it has a structural, mechanical, electrical, magnetic or optical use. The use may be natural as in cellular materials, or it may be to build sky-scrapers as in steel. Matter becomes interesting to materials scientists when the characterisation of its structure and properties, or working out how to make it, leads to an appreciation of its suitability in an existing role, or the discovery of new applications for the material. When this happens we are all happy to call it a material. To illustrate how our perceptions shift consider nitrogen. Very few would call gaseous nitrogen a material. But liquid nitrogen is a useful coolant, and I expect its thermal conductivity and specific heat have been measured. Solid nitrogen may exist on the surfaces of some remote planets, and this raises questions of interest to earth scientists about solid nitrogen as a material – e.g. its elasticity, plasticity, fracture and creep properties. Even nitrogen becomes a material when it is endowed with properties that make it useful as a coolant to us on Earth, or that raise questions about its role in processes on the surfaces of other planets.

All matter is potentially 'a material'. Whether we decide to call something a material depends on whether its structural, mechanical, electrical, magnetic or optical properties enable us to understand an existing role, or to suggest a new role, in some phenomenon or process. These are often called 'engineering' properties of materials, but the function they enable may be in biology or geology as well as traditional engineering. I believe the idea that a material must, by definition, enable some 'engineering' function is what delineates materials science more than anything else. For instance, materials scientists are less concerned with the science that physicists have done on liquid helium and chemists are still doing on gases. Nonetheless, there are vast areas of overlap between chemistry, physics and materials science.

2.2 So what is materials science?

I have argued in §2.1 that materials are a sub-set of all matter. They are distinguished from other matter by their engineering properties, which enable some function or process. I am using 'engineering' in the broad sense of the previous paragraph. It follows that the science of materials is ultimately driven by existing or potential applications of materials. However, those applications are not necessarily industrial; for example they may be biological or geological. When one is engaged in materials research one often loses sight of the applications of the material one is studying. The science becomes so engrossing and demanding that it takes over and applications recede over the horizon. But existing or potential applications must be there because in the final analysis they define the territory of a materials scientist. This is a point that should never be lost in our teaching of materials science, even if we sometimes lose sight of it in our research. It is *not* a point of political correctness. It *is* a logical requirement that follows from the distinction between a material and matter that we would not call a material.

What constitutes the science of materials? Perhaps the simplest way to answer this question is to look at what materials scientists do. First, they determine the *structure* of materials. Second, they measure *properties* of materials. Third, they devise ways of *processing* materials, i.e. creating materials, transforming existing materials, and making useful things out of them. Fourth, they think about how a material is suited to the purpose it serves already, and how it may be enhanced to give better *performance* for particular applications. Each of these four activities is intellectually challenging and there are many materials scientists who are fully stretched not being engaged in more than one or two of them. But what makes materials science especially interesting and rewarding is the fact that these four activities are very dependent on each other. Indeed, this is what elevates the status of materials science to a discipline in its own right, apart from but drawing on chemistry, physics, engineering, biology, earth sciences and mathematics.

A full specification of the structure of a material generally involves a wide range of length-scales, from the atomic, to the microstructural and macroscopic. Structural features at all these length-scale frequently have a profound effect on the properties and performance of the material. Often the principal properties of interest are mechanical, electrical, magnetic, optical or thermal. The creation of materials is an enormous field spanning biological processes such as the growth of bone, organic chemistry for the synthesis of polymers, processes inside the Earth for certain minerals, chemical metallurgy for the extraction of metals from ores, sol-gel techniques, vapour deposition techniques for many electronic materials and devices, aerosol production of oxide powders, and many more. Materials may be transformed by a wide range of methods including heating them, working them mechanically, subjecting them to different chemical environments, and subjecting them to electric or magnetic fields. There are many ways to make useful things out of materials, some of which are quite specific to a particular class of materials. They include rolling, extrusion, machining, grinding, forging, forming, injection moulding, casting, sintering, deposition from liquids or vapours and many others. Again, there are crucial links between the structure and properties of a material and the methods one can use to make useful objects out of it, and *vice versa*. The aim of understanding the links between the structure, properties and processing of a material is to understand how and why the material fulfils its intended purpose, or how its performance may be enhanced. The performance or function of the material is the driver for working on its structure, properties and processing, and measuring its performance is how one judges overall success or failure of the entire enterprise.

3. Aims of a degree in materials science

The subject-specific aims of a degree in materials science are to understand the structure, properties, processing and performance of the principal classes of materials, and to understand and exploit the relationships between these four aspects of materials.

I doubt that this is a very controversial statement, and I hope §2 has convinced any sceptics. The definition of the *principal* classes of materials may be more controversial. It is certainly more subjective, because it depends on one’s point of view, and that of governments, industry, etc. One consideration is whether we should focus our teaching on (a) the materials and technologies of traditional UK materials industries, or (b) we should be more independent and include new materials and technologies (such as materials for nanotechnology) where the UK has lagged behind. A more difficult point is whether we should include major classes of materials that have not appeared in traditional materials science degree before, such as foams, emulsions, foodstuffs, cosmetics, aerosols, granular materials, and more. These are all very interesting and important materials, with a lot of science behind them, and there are huge companies like Unilever, ICI and Zeneca who are dependent on them.

A degree structure comprising a core course followed by options enables one to separate the conceptual foundations of the subject from particular classes of materials. The question of which classes of material to treat is then a question of the range of options that are made available.

The question is what objectives do we wish to set for the core course?

4. Objectives of a core course

Starting from the aims stated in §3, can we define a set of objectives for a core course that will enable the aims to be achieved? A moment's thought will reveal just how difficult this is!

I believe the following objectives are consistent with the above thinking:

1. To understand the design, selection and processing of materials for a wide range of applications in engineering and elsewhere.

2. To understand how and why the properties of materials are controlled by structure and bonding at the atomic-scale, and by features at the microstructural and macroscopic levels.

3. To understand how and why the structure and composition of a material may be controlled by processing.