PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Discussion

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not materials. Most of the science of materials, when it has been concerned with applications, has been aimed at new alloys, improvements by heat-treatment, new microstructures such as fibre-reinforcement, and new fabrication processes. What we may have overlooked is that there is a potential new science, hardly developed yet but of direct relevance to the engineer, which is the science of the performance of materials in engineering service. Perhaps the best example of this is fracture mechanics, developed from A. A. Griffith's pioneering scientific investigations into the nature of brittle cracks, which has now grown into a standard practice in engineering design, based on the requirement that the material in an engineering component should have a minimum fracture toughness, the value of which is governed by the geometry of the component and the conditions of its service.

Need for a science of materials in service

If it were possible to deliver to the engineer various design procedures as explicit as this, for dealing with other problems of materials in service – such as metal fatigue, stress-corrosion cracking, or fretting failure – physical metallurgy and materials science would then be able to make new great contributions to engineering practice. But we are still a long way from achieving this. The necessary science is not yet there.

Many research metallurgists accept this but then go on to delve more deeply into the basic atomic processes of fatigue, or corrosion, etc. Admittedly, we do not yet have a complete understanding, at the atomic level, of the above complex forms of failure in engineering materials, but it may be that such an atomic understanding will not help to solve the practical problem and that the more important thing that is missing at the present time is a rigorous and sophisticated applied science of the uses and service of materials. Let us remember that the application of fracture mechanics does not depend on atomic concepts but on an understanding of the mechanics of a crack in a medium characterized only by its general elastic properties and its measured work of fracture. Similarly, from the practical point of view, the most important scientific discovery about metal fatigue was made long ago, i.e. that this is a type of plastic failure at the surface. A simple knowledge of this alone leads to many useful points in practice, e.g. the importance of hard surfaces, avoidance of soft zones, and minimization of tensile stresses in the surface.

I believe that there is great scope now for taking the existing 'pure' science of materials, as we already know it, and building from it a large new applied science of the performance of materials in service, one that will enable the engineer to get the best out of the materials available to him, even to the extent of encouraging him to adapt and transform his traditional design and constructional procedures to suit the properties of these materials, and to ensure that he will not be disappointed in practice through the unwonted failure of his constructions.

I believe that one of the most exciting challenges now, to the educator in the materials field, is to establish and teach to engineers a 'science of materials in service', comparable to the quite different 'science of materials for service' which he now teaches to metallurgists and materials scientists.

Discussion (Chairman M. E. Hargreaves (*Melbourne University*))

A. Kelly (*National Physical Laboratory*)

For a few more days I can speak as a user, rather than as a producer of trained metallurgists. I want to make a point which I have not yet heard made in this discussion; I want to approach the question of motivation, not in terms of personal ambition of the student as Sir Alan (Keynote) approached it, but in terms of a more altruistic motivation which I think is more important, to the young nowadays. One of the great motivations for people doing engineering is the pull of creativity; the joy of making things; this can be appreciated by the architect or by any of us who try to draw things. There is a real attraction in engineering for the creativeness of a man. Science I believe is motivated by inquisitiveness and so, if one accepts that definition of science, metallurgy is in a very peculiar place, shared only by one other science of which I know.

Consider as you look outside yourself, the stars, the earth you stand on, the rocks underneath, there is perhaps a fluid core in the middle of the earth, there are living things upon this planet – those are things a scientist studies, and none of those was made by man. The difference I think is that metallurgy arose to look at synthetic things. Now that carries with it a very important qualification. Astronomy may be limitless, geology less so, biology probably almost as limitless as astronomy. Metallurgy is not, because the metallurgist looks at synthetic things and those man-made things are made – why? Because the engineer wishes to have them to make other things. On the whole we support a metallurgist because his science supports the engineer.

Now there are two consequences from this which are peculiar to our subject. One, if the young are less motivated to do engineering, then clearly they are less motivated to follow the subjects which support engineering. The second is that since the subject is limited, it does not have the horizons of biology, nor yet of geology, or geophysics. Its (metallurgy's) very own success removes a need for more of us. We have seen in this conference, quite brilliantly, I think, although hedged by details that we do not understand, magnificent achievements. The steel men have told us that they very nearly understand all the factors of that once complex and invisible microstructure; that black box. They can now tell us what are most of the factors involved in producing a strong steel. That success removes the mystery, and once a subject loses the challenge of mystery, it may go the way of other worked-out disciplines.

We are all young as scientists. We are not yet used to the rise and subsequent decay of once-useful and hence fashionable fields of enquiry.

That being said, I see three routes which this corpus of knowledge embracing thermodynamics, microstructure and mechanics, which we call metallurgy, can follow. One of these has been chosen by Sir Alan and that is the last one I would list; it is to support the engineer by producing a prediction, and that prediction will be best used in the forms of constitutive equations. But there are two other routes and, depending on the funding and societal influences (as Cohen calls them) there is still a pure road. That corpus of knowledge has much to say to the geologist, to the person studying planetary structure, particularly the cold planets. It has much to say to the biologists and that is happening in part (e.g. in biomechanics). So there is still a pure road for that corpus of knowledge to follow, and then there is an intermediate one between those two and that brings me to what is the other subject like metallurgy. The answer of course is polymer science. Again a man-made material, but several years behind us in the provision of the microscopic techniques which provide means of unravelling microstructure. Polymer science may join with metallurgy and continue in much the same way as we have seen metallurgy develop.

J. G. Ball (*Imperial College, London*)

I would agree, as a result of direct experience, that it is not a lack of knowledge in schools which results in a lack of students. I think we have to live with such ignorance or such knowledge as exists and I do not think we can much influence the situation. If we look back to the time when we were on the upward grade of recruiting, in the mid 1960s, the factors influencing the flow of students included an overspill from the pure science departments and a desire of many students to keep up their maths, physics and chemistry by taking a subject which included all of these branches of science. Many recruits came because of family connections and there were also people who were intrinsically interested in the subject. In recent times I think that all of these influences have diminished, even the one of family connections and intrinsic interest in the subject. Certainly we no longer get the overspill from pure science or engineering departments because they themselves are looking for entrants. I think Sir Alan has analysed some of the reasons why people go into pure science rather than into our subjects.

What worries me is that not very long ago we considered it to be an absolute necessity, for the students on entry to have a competence in all three basic sciences and that still is expressed in most propsectus', but on the whole it is a forlorn hope that all our students will be prepared in this way. It seems now that our requirement for breadth of scientific understanding is a deterrent to entry into the subject and I do not know what we can do about it.

I feel the situation is going to get worse. The trends of sixth form studies are towards scattered A level subjects, and we might have to be dealing with people coming in with one A level. Such trends are also likely to reflect a lack of rigour in teaching which we have seen developing already. I do not feel that we are collectively approaching this problem, and I think we should be doing so.

D. McLean (*National Physical Laboratory*)

In connection with the development of a science of engineering strength, or performance as Sir Alan (Keynote) calls it, I would like to make three remarks. First, to accomplish such a development material scientists must move on from their preoccupation with uniaxial testing under very constant conditions – constant load, constant temperature and so on – and study the behaviour of materials under conditions which epitomise those of engineering service, such as under multi-axial stress, variable load, combinations of conditions etc. To some extent this involves going over the work which engineers did about the turn of the century and expanding it to suit modern conditions with the outlook of a modern materials scientist. Secondly, it is easier for materials scientists to learn engineering than the reverse, the reason being that a lot of engineering is well codified, is well digested, well condensed and well written up in text books. Quantitative materails science, on the other hand, is quite a young science which has developed during the last 25 years, and is not nearly so well digested and well written-up in text books. Thirdly, the time for such a development is ripe, partly because the problems for which engineers have to design are so complicated that what we might call the existing empirical methods are often unsatisfactory. I think there is a parallel with the relation that existed a century and a half ago between elastic science and engineering, in that the science of elasticity had then been developed by Coulomb, Poisson, Young and others, and had just begun to reach engineers, whose constructions eventually gained immensely. However, the process of being assimilated by the engineers took a very long time. Realization of the parallel should help to shorten the delay in the application to engineering design of quantitative materials science, to produce a science of engineering strength.

R. W. K. Honeycombe (*Cambridge University*)

Much has been said about the present day student and civilization by Sir Alan (Keynote) and others, but I would like to make one point about the modern student that I think points to a paradox, and that is, despite the challenges to authority, students are, on the whole, more dedicated to service of the community. There is a greater social awareness among students these days, than say, 20 years ago. Now this means that students want to do work which is clearly of need to the community, for example, they are prepared more readily to embark on applied science if they have the opportunity. They no longer automatically travel the road of pure science as a first choice. I have talked to many students in Cambridge who have reached the end of their second year, when they have to choose what to do in Part 2, their final undergraduate year. I find out from them why they often change from physics to metallurgy, and the answer is very frequently that they want to do a subject which has direct relevance to the community at large. If this is so, why are the numbers of applied scientists falling in many places? At Cambridge we are suffering much less, so I conclude that we must attribute some of the blame to the mechanics by which the options are presented to students. The students become aware of applied science not at school, but by the time they reach the middle of their University courses, which is the most appropriate time they have for making a decision whether to be an applied or a pure scientist. I think the conclusion from such observations is that we must displace this decision from the sixth form at schools. Sir Alan has suggested one way of delaying the decision namely until after the first degree. In ideal circumstances that would be the answer, as it was in the States for many years, where many of their distinguished applied scientists were originally pure scientists. However it seems to me that we cannot afford, at the moment at least, to have as the main route to technology a first degree in pure science followed by further training in applied science, furthermore, we might lose people in the transition. We have got to structure more courses in a way to encourage a good entry of scientists, and allow technological options to be decided on in mid-course involving a smooth transition from pure to applied science.

Sir James Menter, Treas.R.S.

Bilby (discussion 4) remarked that the areas of science and technology we are dealing with here can be tackled only through large teams from a variety of disciplines working together.

Speaking as an employer of substantial numbers of graduates I can confirm that but wish to point out that this sytem of working through committees and the like is forced on us by the intense specialization of the individual and, with a relative scarcity of graduates with the ability to comprehend a variety of disciplines, design and project work tends to be hindered by all the well known shortcomings of the committee system. I am therefore attracted to Sir Alan Cottrell's idea (Keynote) for creating large schools of science (and presumably also engineering) in Universities where students can study a selection of specialist disciplines in some depth. This system has greater potential than existing arrangements for producing a greater proportion of people with broader competence, having the character of the Prince Charming to which I referred in my talk.

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J. F. Lancaster (*Kellogg International Corporation*)

The hydrocarbon processing industry is a major consumer of fabricated products and, in the United Kingdom, if we make proper use of North Sea oil and gas, will become increasingly important in this respect during the next few decades. It is therefore essential that metallurgists, both in the academic and in the practical fields, understand and respond to the particular metallurgical needs of these industries.

Although the industry's problems are common to those of the engineering industry as a whole, special considerations arise in the specification and construction of the process equipment itself, where inflammable and sometimes toxic fluids are handled and processed. To keep up proper standards of safety in this area required the appropriate techniques of material selection, of quality assurance in manufacture and of operation and maintenance of equipment. It says much for the diligence of all concerned in this industry that the safety record is so good. For example, in the chemical industry the number of fatal accidents per employee is 3.5 per 10^8 h as compared with 4.0×10^8 for British industry as a whole, 40×10^8 in coalmining, and so forth.

There is, of course, considerable incentive to maintain or improve such high safety standards, quite apart from concern for the safety of individuals. The scale of single stream process units increases with time, and incidents that can lead to an unsafe situation may also lead to periods of increasingly costly downtime. Major incidents, such as the Flixborough disaster, also have an unfavourable political effect on the industry, making it more difficult to obtain suitable sites for process units and potentially attracting restrictive legislation regardless of the fact that the industry's general level of safety is good.

Metallurgists and materials engineers can make an important contribution to safety in hydrocarbon processing. Not all unsafe incidents are caused by metallurgical defects: indeed, the majority of such incidents are complex in origin and it is rare to be able to isolate a single well-defined cause. Nevertheless, the failure of a piece of metallic equipment is a feature of most accidents and it is most important to ensure that both materials and fabrication are to standards that are sufficiently high to exclude the metallurgical factor as a primary cause of failure.

This is an easy generalization to make. It is more difficult to define precisely what steps should be taken in metallurgical education, research and development to promote higher standards of reliability in this field. To do so would require much better information about failures than we presently have. Nevertheless, I think the metallurgical profession might profitably give attention to the problem of training in materials engineering.

Materials engineers in the hydrocarbon processing industry are usually metallurgists, chemical enginers or mechanical engineers who have elected to specialize in materials. On-the-job training is the normal rule, but it is not particularly easy to acquire the necessary information. This is especially the case with material selection. Chemical engineers are sometimes given a course in this subject, but it is at present tending to be crowded out of the syllabus. It is not, so far as I know, included in any of our undergraduate courses in metallurgy, nor are there any short courses available in material selection in the United Kingdom. Furthermore, there is no worth-while textbook on the subject. With the exception of the lectures included in corrosion courses organized by such bodies as U.M.I.S.T. and the City University, the materials engineer must learn his trade as best he can, obtaining information about the experience of others, mainly from U.S. journals, such as *Corrosion*, *Materials Protection* and *Hydrocarbon Processing*.

The process industries do not at present employ many materials engineers but the demand for such technologists is going to increase in the future. It might be profitable, therefore, for the metallurgical profession to consider how a better transmission and exchange of information on materials engineering and materials selection can be achieved.

The following two contributions were written after the meeting:

K. E. Easterling (*University of Lulea, Sweden*)

Of five technological universities in Sweden, four have departments of engineering materials, i.e. for the teaching of engineers with specialization in materials, and there is only one department of physical metallurgy. Thus the important interaction between engineers and materials specialists is strongly recognized. Engineers in most cases follow general engineering courses in the first two years and specialize in the area of their choice in the final two years. Every individual course is followed directly by an examination, so there is not a general examination session covering a whole year's work. There are no honours degree systems (as followed in Britain); the philosophy here is that graduation engineers have all broadly acquired the standards expected of the school concerned, and as such start out on their careers on a more or less equal basis. On the other hand, individual examinations are graded, so some recognition is made of talent.

E. R. Petty (*National Institute for Higher Education, Limerick, Ireland*)

We should remember that the word 'generalist' has come about to some extent because of the particular historical way in which we have packaged knowledge. Were we to start reorganizing the information available to mankind we might well never use the words metallurgy, polymer technology, production engineer. In fact, words like chemical engineer or systems engineer might well say it all. Or possibly, different groupings of topics might be more appropriate and we might talk of departments of tribology or thermodynamics. In view of the cries from industry and the ways in which Britain has fallen behind in the technological race, the time is probably long past that we should have stormed the barricades between rigid disciplines.

Further advantages of the broader degree scheme are related to the greater breadth of topics being taken at G.C.E. A level these days and also the necessity to give students more time to make up their minds about a chosen career path.

One major criticism of the generalist approach is based on an implied reduction of intellectual level – the so-called 'depth' of treatment. In the system proposed this may be readily avoided by cutting down on the total number of pieces of information considered – after all any degree scheme in however 'narrow' a subject can no longer hope to pack in the total sum of human knowledge in the field, so a selection is always necessary. In the generalist approach one simply broadens the range of options from which the selection is made. While on the topic of depth, it has always been my experience that students find it more difficult to assimilate and correlate material from diverse fields than to go more deeply into one specialist area. Deeper specialization can always come about through continuing education, either formally or during normal self-education at the place of work.

At the National Institute for Higher Education we have set up such a system of education. Being a new educational establishment we are not bound by tradition and, while this has many disadvantages, it does allow us the freedom to experiment with new ideas. One of these is the setting up of a degree programme in Materials and Industrial Engineering administered by an

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interdisciplinary committee with representatives from Business Studies, European Studies, Electronics and Mathematics as well as the engineers. We have produced a four year sandwich-type course (ten academic terms plus a total of 12 months in industry) with the first two years devoted to basic science and engineering. The two final years cover a range of elective topics many of which are sequential and interrelated.

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