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

Discussion

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atomistic basis of the engineering properties of materials. Rosenhain justified the separate identity of physical metallurgy on the basis of a need to distinguish it from what he called the 'old metallurgy'. It seems to me timely for it to be fully assimilated into a 'new metallurgy' which in turn will increasingly assume an even broader aspect as materials science and technology.

Within this new metallurgy there is a pressing need for the distillation of knowledge gained from atomistic studies into 'general principles expressed in language which engineers can understand' – to quote Cotton again. In approaching that task it is important to distinguish those problems where the unit atomic processes have a direct bearing on engineering properties from those in which the unit processes can be adequately treated on a statistical basis and described by the equations of continuum mechanics.

The new metallurgist will increasingly approach materials development as a total problem of liquid physics and chemistry, solidification control and shape control. He may well encounter, coming from the other direction an engineer who will be increasingly knowledgeable about microstructures and materials manufacturing processes, wishing to spell out detailed requirements, hitherto regarded as the preserve of the metallurgist. This is not to imply that all practitioners of metallurgy and engineering will be expected to be competent in all aspects of the other's trade. Of course the individual subdivisions of both will continue to be essential for the advance of knowledge and of practice. What I am really calling for is an increasing number of designers who can deploy the accumulated wealth of materials knowledge to the creation of cost effective and energy conservative artefacts. How are we to breed these designers? That is a question which I must leave to Sir Alan Cottrell in the next session of the conference.

Discussion (Chairman R. W. Cahn (*Sussex University*))

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

I was naturally extremely interested in the points which Sir James (Keynote) raised on the re-unification of the field of metallurgy, and particularly as he started from the point of view of the definition given by Rosenhain in his 1914 textbook. We have been trying to do this for the past 15 or 16 years in Imperial College. Appropriately, it was in the forerunner of Imperial College, the Government School of Science Applied to the Arts, that the teaching of metallurgy in this country really started, initially to exploit the mineral resources of the top 23 cm of the surface of this country. At that stage, it was the winning of the primary metal from the mineral that dominated, and it was Percy's task to organize teaching of this subject when he came from the practice of medicine in Birmingham, to take up the chair of metallurgy in the Government School. This Government School, as a result of a wrangel with T. H. Huxley, became the Royal School of Mines. Percy left in rather a huff because of an argument with Huxley, but his successors such as Sir William Roberts Austin and Sir Harold Carpenter, in fact devoted their energies to what was essentially physical metallurgy. While this was going on, the teaching of chemical or extraction metallurgy extended into the teaching of chemical analysis, which was practiced near the mine where the primary metal was extracted. Subsequently a lot of the teaching spread from the Royal School of Mines to the growing number of academic departments in the country. The chemical side of metallurgy tended to be rather arid, concentrating as it did on chemical analyses which were pursued by ancient methods bearing no relation to the interesting physical techniques which we have at the moment. Thus, in the minds of many students, physical metallurgy burgeoned forth from the exploitation of X-ray and microscope techniques, and the development of dislocation and alloy theory to become an interesting and dominant topic in metallurgy teaching.

With the more recent development of chemical metallurgy in terms of thermodynamics, a much more interesting scientific basis was achieved, and it is the exploitation of that which, led by Professor Richardson, we have been attempting for the past 15 or so years. I do not think Sir James means to confine chemical metallurgy solely within the extraction context; he means something much wider. The chemistry of materials can, and should, embrace a much wider range of science than it does at present. But when we attempt to include this in a teaching curriculum, we are in danger of forcing the student in too many directions. It is essential, and I think this also comes from what Sir James has said, that you not only talk about chemistry and physics, you must include someting about engineering properties, fluid flow, heat transfer and so on. The big danger is that the student finds such diverse matter indigestible. We found this continuously during our attempts to integrate this very wide range of science and technology into a single undergraduate course. The alternative is to go to a general type of degree and there are many arugument in favour of this, but where joint honours degrees have been tried in the past, they have not been noticeably successful in attracting the best sort of students. We have consequently been very wary in moving in this direction. However, the climate is moving again in this way, and it might be possible to exploit the build up of modular degrees. Nevertheless, the chemist and the physicist have distinctive ways of thinking and they do not always easily marry together. This is a serious problem which should not in any way be swept aside. If you try to develop this integration where there is an intense and large research activity, you are almost inevitably having to do it with specialists, who have their own special interests to pursue. I personally think that we might get the breakthrough by giving more recognition and status to devoted teachers who are not married particularly to one branch of the subject.

C. Edeleanu (*Imperial Chemical Industries*)

If Sir James (Keynote) had added to the list of subjects he has mentioned as being related to each other, 'tribology', 'soil mechanics' and 'noise and vibration' he would have described a service which goes by the name of Engineering Technical Services in that part of I.C.I. in which I work. Since we try to provide an integrated service to our engineering colleagues I cannot but agree with Sir James that none of us can afford to take a narrow view about our particular field of specialization. To give an example; the man concerned with corrosion could resolve some of his problems by specifying silicon iron but that only creates a problem for the metallurgist, an impossible nightmare for the welding engineer and for all the other people down stream from him. The essential thing for a service of this type is to act as a team and to have respect for the difficulties which each one of us can create for other members of the team by insisting that what is the ideal way to resolve our bit of the problem is also the ideal solution for the task as a whole. This is the way we try to resolve the problem associated with the interfaces between the various specialist technologists but there is perhaps a more important interface to think about and that is the one between the scientist and research technologist on the one hand and the engineer on the other. From things said during this meeting one does detect a love–hate relationship across this interface and perhaps a degree of ignorance about the method of crossing it.

To understand the problem it could help to remember that the engineer, who is the man who ultimately gives physical expression to the knowhow of technologists, needs to think convergently if he ever is to get the hardware built in a reasonable time and to the customers expectation and much as he may wish to understand every bit of technology he uses he seldom can do so not because of an intellectual weakness, but because life is too short. The scientist and technologist on the other hand is a divergent thinker and especially so if involved in R. and D. and is interested in some of the detail behind the broad facts with which the engineer is concerned.

He has to be like that if he is to be any good at his job. There is therefore a great deal of scope for misunderstanding between the man who simply wants to know what he has to do next and the man who wants to explain why things are as they are and to provide the detailed information about the pros and cons associated with each one of the available options, so that the engineer can use his judgement and make a decision.

One can argue that people should not fall in either of these categories and should be able to switch from one way of thinking to the other but why demand this versatility of people if this is not a real need and especially since it is uncomfortable for most people to make the switch. This is especially so since there are some people who seem to be especially skilled at making this very switch in the way of thinking and can and do cross the interface quite happily. I like to think of such people as being 'brokers in technology' and I think we ought to recognize them, and accept that like other brokers, they have an important role to play. Once you use such a broker you will find that it is easy to cross the engineer/technologist interface if the man is any good.

That is not quite the end of the problem however, because we who live at this interface between engineering and technology have a lot to learn from each other and we need to develop our skills and perhaps formularize our methods of bridging the gap between science and technology. I do not know if this is possible, but we could improve our skills so that science could find its way into hardware a bit more rapidly than it now does.

If I may suggest, this could be a surer way of making progress than by attempting to teach metallurgists how engineers design, estimate, procure, inspect, construct and generally manage a project or by teaching engineers the mysteries of dislocations, chemistry of corrosion and physics of g.r.p.

M. E. Hargreaves (*University of Melbourne*)

It is rather strange for me to hear this discussion because in our University these various branches of the subject have never diverged. Since 1925, when we established a metallurgy course within the engineering faculty, all students have been taught, not only chemical extraction metallurgy, electrometallurgy and physical metallurgy, but also ore-dressing as well. I think this is a very good thing coupled with the ability to specialize in one of these branches in the final year. Now the wheel goes a full circle some times because in lecturing to my final year class in physical metallurgy last year, I was able to point out to them a paper in an ore-dressing journal which showed the influence of vacancy content in galena on its surface activity and therefore its behaviour in an ore-dressing process. So I think it is possible to teach an integrated course in metallurgy if specialization allowed and we have jogged along quite happpily like this for 50 years.

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

There seems to be a general feeling that physical and chemical metallurgy should reunite. I hold the view that even this is a somewhat introverted outlook in this modern age and I make the plea for a further breaking down of interdisciplinary barriers.

Metallurgists now tend to identify themselves with the whole range of materials available to the engineer and, as engineering is our raison d'être, surely we should think of ourselves as *materials engineers*.

Materials engineering could legitimately include mining, mineral processing and extraction, through chemical engineering and process engineering into production engineering. This latter area includes the organization and management of industry; one hears so many pleas for scientists and engineers to come down to earth and accept the basic fact that industry has to make money and be competitive. This means a rudimentary understanding of such topics as industrial psychology, cost and inventory control, operations research, at least to a level which allows 'experts' in different areas to communicate intelligibly with each other.

The training of a materials engineer would entail a broadly based first degree with a foundation in physical and chemical principles together with some of the more important engineering and technological applications, followed by a limited number of selected topics taken to greater depth in the final year. Greater specialization, if required, would be done in post-graduate and/or post-experience programmes of study. This 'continuing education' is a vital part of the training of any scientist/engineer now that the half-life of technological knowledge is less than ten years.

It seems to me that the flexible system outlined is more relevant to the modern world than the over production of narrow specialists, directed in the main towards university research and teaching, to which we have become accustomed.

N. L. Parr (*Ministry of Defence, Procurement Executive*)

As a move towards a common language between materials science and technology and engineering practice, more research is required on sensors for assessing the microstructural and macrostructural performance of components and structures under operational conditions. This would be of equal importance to materials development, design, cast and safety of ownership. A start has been made on acoustic emission analysis for structures, and monitors for tribological deterioration; but more requires to be done in this highly complex area of realistic characterization. This was stated by Sir James (Kenyote) in terms of a greater need for physical studies of materials under dynamic conditions.

M. G. Gemmill (*Central Electricity Generating Board*)

I was very cheered by the beginning and the end of Sir James' lecture (Keynote) because, having been subject to a University education where I was expected to study not only the chemical and physical metallurgy but also physical and inorganic chemistry I see no problem frankly in what he now claims as the educational requirement for the future metallurgist. If a person is incapable of dealing with that scope he or she should not be there in the first place. So we come back to the general argument which Sir James has put forward. After years of worrying about the over-specialization of our metallurgists, it would be very good indeed if we lose that.

Earlier two of my C.E.G.B. colleagues, Wyatt and Barford, made very honest admissions of the difficulties facing R. and D. people in transmitting their knowledge in a way that allows me, as the Boards materials engineer, to translate it into our manufacturing industry, so that we achieve more reliable components. The situation can be considered in terms of Cohen's chain of events from physical metallurgy, to the engineering end product. What we have to ensure, I would suggest, is that all the links in that chain are strong, so that we end up with an effective communication system.

The problem is how to deploy the sources of knowledge in sensible relation to the vested interest. For example, and this is quite hypothetical, it might be that organizations such as the British Steel Corporation and C.E.G.B. could find themselves in a situation where they carry more resource to contribute to the technical solution of a problem facing a component producer who lies between them, and bears the commercial responsibility. Rather than complain about the fact that he had misplaced manpower resource, I would suggest that we should be able to find ways of transferring this knowledge that give an individual both career and job incentive. This will require device, such as staff secondment or funding either by primary metal producers or ultimate users of an under-resourced component producer.

In the example mentioned, this would allow B.S.C. to promote the use of their very capably researched findings on steel metallurgy and C.E.G.B. to see for example, practical return for their equally well researched work on the effects of impurity elements in regard to welding technology.

M. Cohen (*Massachusetts Institute Technology*)

I am rather dubious that placing physical, chemical, and process metallurgists in the same department will achieve the unity and the interplay required for the two-way flow of knowledge between metal science and human needs. There are already too many instances where this juxtaposition, although desirable in itself, has not proved sufficiently attractive to students or effective in industry.

Perhaps the time has come to consider a systems approach to metallurgy or to materials more generally (at least for some students) in which the field is viewed with 'telescopes' instead of 'microscopes'. At M.I.T., we have begun to work on this different focus, taking advantage of the impressive progress that has already been achieved in other branches of engineering, where some of the core subjects now emerge as applied probability, optimization theory, and microeconomics.

J. H. van der Veen (*Hoogovens, Holland*)

Within the scope of the discussion about interface between 'process' and physical metallurgy and the merits, or otherwise of combining these disciplines into one, I would like to draw attention to the factor 'motivation'. I think, in practice, more attention could be paid to motivation of 'process' metallurgists in the direction of making steel for future products; future performance of a product. Being far away from the final product, in terms of processing stage, and far away from the customers' needs, process metallurgists otherwise perhaps might pay too much attention to steel making efficiency and other (though important!) more 'local' problems.

G. G. Saunders (*Whessoe Ltd*)

Following up the point of cost effectiveness, may I offer a suggestion towards the future role of physical metallurgy in relation to the technological objectives of this country during the next 25 years. If one studies the many published papers on physical metallurgy, one observes that these are concerned mostly with what one might consider as high technology; such as might be associated with projects like Concorde. Since the bulk of this country's prosperity relies very heavily on the 'low technology' associated with the fabrication of iron and steel, may I suggest that those responsible for directing future studies in physical metallurgy, consider the considerable benefits to be gained in knowing more about such seemingly ordinary materials as mild steel.

B. A. Bilby (*Sheffield University*)

May I first comment on the multi-disciplinary approach needed to make progress with complex problems. As more disciplines are demanded, the teacher may seek to encompass them by a course which is both more diluted and more theoretical. However, not only is the proper theory often not yet available, but a false picture of the discovery process itself may thereby be created. A thorough discussion of fewer topics in their correct historical perspective is more likely to instil that competence in the critical handling of the interaction of theory and experiment which is necessary for progress. To tackle the problems then, there must be team work, with specialists in different fields cooperating, although ever team must, of course, have a leader.

Despite these strictures on theory, I believe it has an important role to play not only in the microscopic fundamentals of materials science, but also in the interaction with the engineer (the ubiquitous dislocation is also relevant to both fields). One of the great thoughts of this conference I find in the maxim of Francis Bacon quoted by Brown (2.7) 'Truth will sooner come out of error than confusion'. This is apt for some of the activities of Rosenhain himself, as we heard from Kelly (Centenary lecture). A prime task of the theoretician is to reduce the confusion; if I may exaggerate Willard Gibbs a little, theory is supposed to make a thing so simple that you wonder why you have not already looked at it this way yourself (and that is always the feeling I have after hearing a lecture by Sir Alan). A classic example of what I mean by making things simple is to be seen in the rise of linear elastic fracture mechanics. The important simplifying concept here is the stress intensity factor K, which is the leading parameter in the characterization of the crack tip stress field. A critical K criterion for crack extension includes the necessary energy balance condition of Griffith, but in a more convenient and powerful form. The engineer can use it to infer that, other things being equal, K determines the physical processes at the tip, so that if fracture occurs at a critical K in the laboratory, so also will it do so in a structure. Thus a basis for practical testing is established. When fracture occurs only after considerable plastic deformation, the situation is more complicated. Here we have a current problem, with its attendant confusion. This is not the place to discuss it in detail, but theory can help by specifying precisely under what conditions the present attempts to characterize the fracture process will be valid, and by looking for new methods of doing so. Finally, it is clear from the discussion that an important concern for the future in the theory of fracture must be to pass from a fracture 'mechanics' to a fracture 'thermodynamics'; or, rather, to an integrated treatment which takes account not only of thermally activated processes, but also of electrochemistry.

W. H. Eaton (*University of Surrey*)

At the end of the conference I had an impression of pessimism about the future of physical metallurgy; a sensation of the end of an era. It appeared that the only path for the physical metallurgist was to take his well tried methods of structure-study and apply it to the correlation of structure and properties in non-metallic materials.

This is certainly a field that offers an enormous scope for his talents and would enable him to assist the chemists and the engineers who develop and use these materials.

However, while the mechanisms in structures leading to properties in metals may be understood, there are still large areas in the physical metallurgy field to be studied, particularly in persuading the 'understood' mechanisms to operate reliably in commercial steels and non ferrous alloys.

In the past, the physical metallurgy of steels was extended by the automobile and aircraft industries. Parts for these industries were small and could be loaded into furnaces for thermal treatments at various stages of manufacture. This initiated studies into the improvement of mechanical properties by controlled solution and precipitation of particles. It was necessary for the particles to be unstable over a range of temperature change otherwise the thermal treatment could not be applied.

The development of the gas turbine, the high temperature boiler and the atomic power station moved the study into the direction of stable steels and non ferrous alloys in which the structure did not change over longer periods of time at elevated temperatures.

In the immediate future the gas and oil pipeline technologies will demand large quantities of low carbon weldable steel leaving a high yield stress, good crack arrest properties and (in some cases) low temperature ductility.

There is still scope for the physical metallurgist to develop steels suitable for pipelines and pressure vessels, and to examine the behaviour of those steels already in service in these structures, to determine if they can be economically improved.

Other participants have already commented on the effects of residuals on the ductility of weldable steels and there is an interesting area of investigation in reducing their effects at low cost.

N. Hansen (*Danish Atomic Energy Commission*)

A large field opening up for metallurgists and engineers has not been touched much upon today: energy production. This field presents us with a number of complicated problems, just a few examples: gas–metal reactions in gas cooled reactors for process heat, materials for hydrogen production and energy storage and temperature and radiation resistant materials for the potential fusion reactor. Due to the pressing energy problem, there may be good reasons to believe that we have a promising future in this area of energy production. With reference to Cohen (this discussion) we might hope that good results in this field in a positive way will increase our interaction with society.