



# A bird's-eye view of materials engineering\*

by G.T. van Rooyen†

## Synopsis

In this overview of materials engineering, the author, drawing on his long experience from his student days until the present (emeritus professorship), briefly recounts the main developments in this field: dislocation theory, fracture problems, and the development of alternative materials such as ceramics and polymers. He then takes a look at the future, in which he foresees a greater demand for materials engineers, and leading roles for universities and technikons in collaboration with industry.

## Introduction

Because of the bewildering rate at which publications on materials in their broadest sense are appearing in the press, it is perhaps an opportune time to reflect on the path along which we have travelled and to consider the road ahead. Worldwide, materials engineering has been identified as one of the growth areas. In more than one way, materials are always the ultimate limitation as to what can be designed and manufactured. The variety of materials available and the service requirements are so diverse that we are faced with a massively complex problem. In theory, it should be possible to have a databank in a computer and software to enable one to select the optimum material once the service conditions have been defined. This, of course, presupposes that there are technical solutions to such problems as fatigue, stress-corrosion, and creep. In practice, however, there are, for example, no fatigue-proof materials, and the problem of fatigue has to be managed in a responsible fashion during both the design and the manufacture of a component and its subsequent use. Even with the most sophisticated analytical tools that are now available, one is astounded by the catastrophic nature of the material problems that are frequently encountered. It is only with the advantage of many years of hindsight that one is able to gain the necessary perspective.

In fashionable subjects such as physics and astronomy, the correspondence between

model and reality is so exact that some people regard nature as some sort of divine mathematician. In the case of the mechanical properties of engineering materials, mathematical analogies have to be used with great caution. The trouble is that, in real situations, the aspects involved are so complicated that they can seldom be represented by a single mathematical model. Structures, for example, can fail in a variety of modes. All too often failure occurs by a mechanism that nobody happened to think of, let alone take into account in the calculations. A deep, intuitive appreciation of the inherent cussedness of materials is one of the most valuable accomplishments of an engineer.

I am one of the old hands, born and bred before the advent of the modern personal computer. I can vividly recall my first introduction to the Whirl Wind computer at the Lincoln Laboratory of M.I.T., where I studied. To tell the truth, I was not really impressed with the halls filled with thermionic valves and the extraordinary amount of programming in digital format that was necessary for elementary calculations. I was, however, fortunate to study under such academic giants as Morris Cohen, Michael Bever, John Chipman, John Wulff, and Egon Orowan. I was fortunate to obtain my first exposure to mechanical properties from Professor Orowan in a two-term course entitled 'The Physics of Strength'.

## Dislocation theory

In terms of mechanical properties, the consideration of deformation maps such as are

\* Presented at the G.T. van Rooyen Symposium 'Materials in Action', which was held at the University of Pretoria on 29th and 30th June, 1994.

† Professor Emeritus, Department of Materials Science and Metallurgical Engineering, University of Pretoria, Pretoria, 0001.

© The South African Institute of Mining and Metallurgy, 1996. SA ISSN 0038-223X/3.00 + 0.00.

# A bird's-eye view of materials engineering

shown in Figures 1 and 2 is a good starting point. In these diagrams, the ratio of the shear yield stress to shear modulus (normalized strength) necessary for plastic deformation of nickel is shown as a function of the ratio of the test temperature ( $T$  K) to the melting temperature ( $T_m$  K) for various rates of straining. Figure 1 shows the mechanisms by which deformation occurs in each zone, whereas the practical operational areas are shown in Figure 2.

One of the interesting aspects shown in these figures is the ideal strength, which is supposedly not sensitive to temperature and strain rate. This represents the ultimate yield strength of a perfect crystal that contains no lattice defects such as dislocations and vacancies. In the early thirties, the large discrepancy between the ideal strength and the actual strength was considered to be due to lattice vibrations, and it

was thought that the ideal strength could be reached by tensile testing at 4 K—the boiling point of liquid helium. Professor Orwan used to tell his class how the first helium liquefier was built and of the utter disappointment when the ultimate experiment 'failed'. It turned out that the strength at 4 K was higher than that at room temperature but was not even close to the ideal value. He never mentioned that it was actually his own experiment that had 'failed'. The failure of the experiment led to a re-evaluation of the theory and to the realization that real crystals are never perfect but contain line defects such as edge and screw dislocations. Plastic deformation was thought to occur by the movement of such dislocations on slip planes at stresses much lower than the ideal strength.

In a short span of time, dislocation theory was developed with a remarkable degree of sophistication. It was soon realized that, at the atomic level, dislocation theory could be applied to explain a large number of phenomena. The initial enthusiasm was heightened by the expectation that the study of dislocation theory would make it possible to calculate mechanical properties from first principles. Dislocation theory was to be material engineering what Einstein's theory of relativity was to physics. What made this development remarkable is that it occurred with very little evidence of the actual existence of dislocations. There were many sceptics, even in the late fifties, who doubted the existence of dislocations. The actual direct proof of the existence of dislocations had to wait for the development of the electron microscope, and I can still remember the first publications of transmission electron-microscope photographs, which showed dislocations as black lines. Much later, once high-resolution electron microscopes had been developed, it was indeed possible to resolve atomic lattices, and actual photographs of dislocations (Figure 3) were published that were almost identical to those drawn schematically some 30 years earlier.

In many ways it turned out that dislocation theory was inadequate to predict actual mechanical properties. Whereas there is no denial that dislocations hold the key to all mechanical properties, it is now realized that most macroscopic mechanical phenomena ultimately depend on the complex interaction of such large numbers of dislocations that it is almost impossible to model the process mathematically with the desired degree of accuracy. Even in this day and age, mechanical properties have by and large still to be determined experimentally.

Another sobering feature shown in Figure 2 is the very low strength that is required to deform nickel at moderate temperatures and at very low strain rates. For most structures to be able to continuously support a load indefinitely without creep, the working stresses have to be very low or, alternatively, the safety factor has to be very high. This requirement is exactly the opposite of the modern tendency to require higher performance and, consequently, higher stresses. By strict quality control of the material, it is today indeed possible to use higher stresses without compromising integrity. However, Figure 2 reminds us that, when the stress levels are increased, the lifespan of a structure is immediately compromised. Looking at the large structures of today, I frequently wonder what will be left of them in, say, another 2000 years' time. That, incidentally, is the age of the Pantheon in Rome, which is still remarkably well preserved.

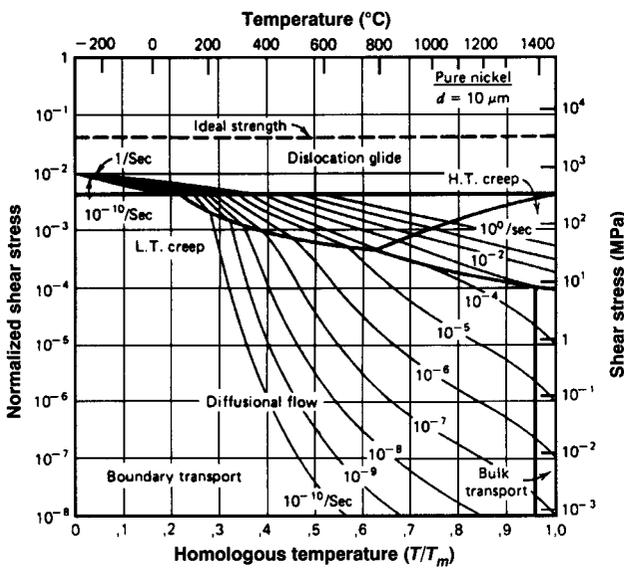


Figure 1—Deformation map for nickel with a 10  $\mu\text{m}$  grain size. Isostrain rate lines are superimposed on the map<sup>1</sup>

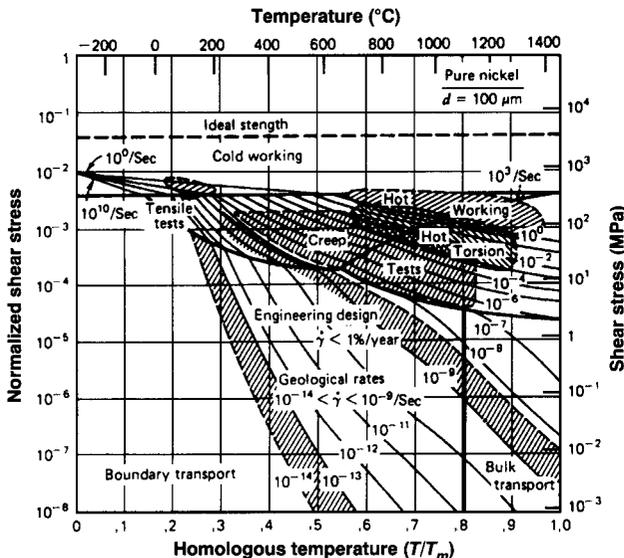


Figure 2—Deformation map for nickel with a 100  $\mu\text{m}$  grain size, showing laboratory test regimes relative to deformation fields experienced by the material<sup>1</sup>

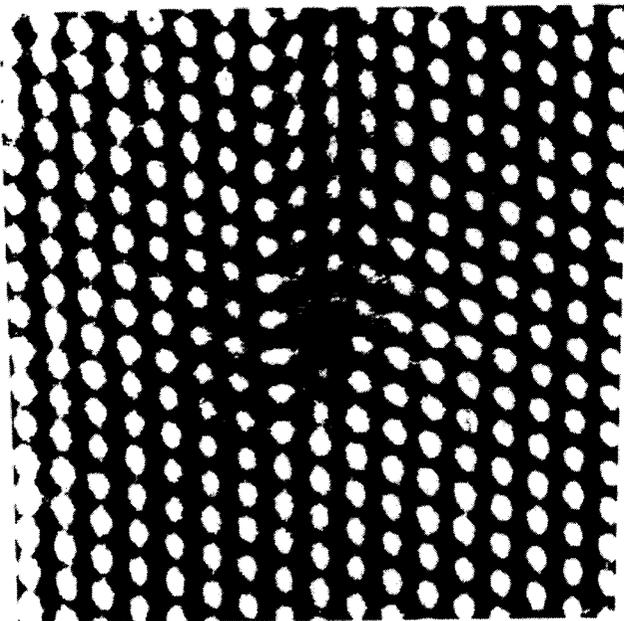


Figure 3—Phase contrast image showing the termination of a stacking fault in silicon. The extra atomic plane enters from the top of the image and ends at the centre at the position of a Shockley partial dislocation<sup>2</sup>

**Fracture**

Historically, eras have been classified in terms of the material that was dominantly responsible for their technological advancement, such as the stone, bronze, and iron ages. However, developments in materials have been so numerous and diverse lately that the present age could be described by such terms as the plastic age, the composite age, or the semiconductor age, depending on one's point of view. One of the great benefits that metals brought to the stone age was the capability of a material, when overloaded, to deform in a plastic fashion without breaking in a brittle manner. The problem of brittleness, however, has not disappeared. As a matter of fact, it has become one of the ultimate limitations in the development of high-strength materials. The study of brittleness or, in more sophisticated terms, fracture mechanics, has become one of the major thrusts in recent years.

It was only around 1850 that engineers started to calculate the stresses in structures. The thickness of a section depended on the working stress, which was the tensile strength divided by the safety factor. To make quite sure that the structure would be safe, engineers normally used a fairly high factor of safety, which ranged from 4 to values as high as 20. If a safety factor of 20 is really necessary, the whole basis of the initial calculation makes no sense, and the safety factor can, in fact, be regarded as a factor of ignorance. Initially, when structures that had been designed with such high safety factors failed, defective materials were usually blamed. Again, this notion is untenable if one considers how defective the material really has to be to actually fail when designed with such high safety factors. The real reason why a component can fail at stresses very much less than the tensile strength is that failure can occur by the catastrophic propagation of cracks. The component then fails in a brittle mode in spite of the fact that, during tensile testing of the material, it will elongate considerably in a ductile fashion before fracturing.

Steel in particular, but also other high-strength materials, has a dual character in that it can fail in both a ductile and a brittle manner. This awareness is of critical importance in the engineering application of any material. Whereas ductile behaviour is usually presumed to be the norm, brittle failure can be induced by any of the following, or by a combination of them: low temperatures; high rates of loading; the presence of stress raisers; other internal discontinuities produced during casting, welding, or forming; and the presence of cracks due to fatigue, creep, hydrogen embrittlement, and stress-corrosion cracking, to name only a few.

The dual mode in which steel, for example, can fail is clearly illustrated by the Charpy impact transition curves shown in Figure 4. Below the brittle transition temperature (BTT), the steel fails in a brittle manner by decohesion along atomic cleavage planes, absorbing only a minimal amount of energy. At temperatures above the BTT, ductile failure occurs by micro-void coalescence, absorbing a high amount of energy. Most materials are characterized by such transitional behaviour. Glass, for example, becomes ductile at elevated temperatures above the glass temperature, whereas rubber becomes highly brittle when it is cooled down sufficiently. Most, but not all, face-centred cubic metals such as copper and aluminium are not characterized by such transitional behaviour, and remain ductile even when cooled down to temperatures as low as 4 K. They are, however, the exception rather than the rule.

The influence of cracks on the strength of a material is clearly of critical importance in this respect. Back in 1913, C.E. Inglis showed that the local stress at the tip of a crack or other sharp discontinuity can be many times higher than the average stress. This is clearly demonstrated by photo-elastic material under stress, as shown in Figure 5. Inglis<sup>5</sup> showed that the stress at the tip of a discontinuity with a radius  $\rho$  and a depth  $a$  is  $[1 + 2\sqrt{(a/\rho)]$  times greater than the local applied stress. For a true crack, the radius of curvature at the tip of the crack is very small (probably only 2 to 3 interatomic distances), and the actual stress at the tip of a crack can be 100 to 1000 times greater than the average applied stress. Obviously, if this were true in the case of metals, the strength of a structure would be reduced dramatically by the presence

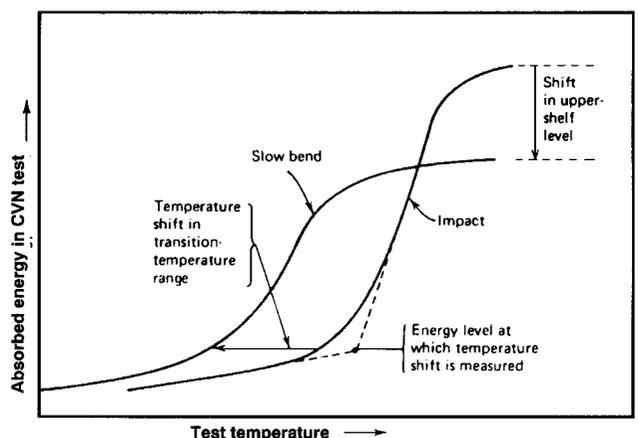


Figure 4—The energy required for fracturing versus the testing temperature. Note the higher shelf energy, as well as the increase in the brittle transition temperature<sup>3</sup>

## A bird's-eye view of materials engineering

of even very small cracks. In actual fact, plastic deformation at the tip of a crack usually, but not always, blunts the crack and in that way relieves the high local stress. Such a crack would then be able to tear slowly in a controlled fashion at fairly high stresses. On the other hand, the tip of a crack may not be blunted to any considerable extent and would propagate in a catastrophic brittle manner at an applied stress very much lower than the tensile strength.

The solution to the question as to when cracks would be safe or when they would result in catastrophic failure was worked out by Griffith<sup>6</sup> in 1921, and is expressed by a beautifully elegant equation:

$$\sigma_c = [(2E\gamma)/(\pi a)]^{0.5}$$

In this equation,  $\sigma_c$  is the critical stress at which a crack of size  $a$  will propagate in a catastrophic fashion.  $E$  is the elastic modulus and  $\gamma$  the surface energy. Expressed in words, the Griffith equation implies that a crack will propagate catastrophically when the strain energy released by an incremental amount of crack propagation is more than the surface energy required for the same incremental amount of crack propagation. In essence, it boils down to an energy balance, which is one of the most basic approaches that can be used to the solution of any problem in mechanics. At the time (1921), Griffith was still a young man, and the fact that he expressed his results in terms of strain energy, rather than stress, resulted in an almost complete lack of attention to his equation. As a matter of fact, if actual values of  $E$  and  $\gamma$  for iron, for example, are substituted into the Griffith equation, completely ridiculous answers are obtained. For many years, it was therefore believed that the Griffith equation could be applied only to ideally brittle materials such as glass.

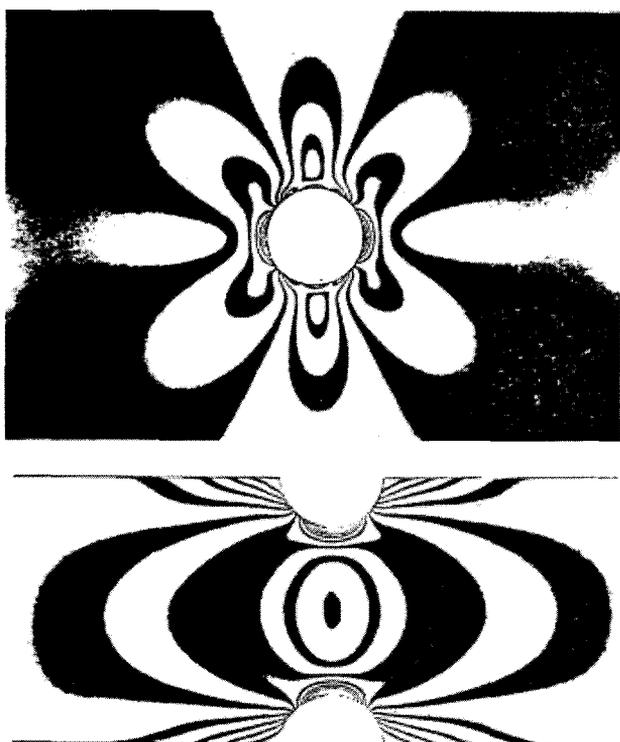


Figure 5—Stress concentration around a hole and at a semicircular notch in a tension bar<sup>4</sup>

It was only thirty years later, in 1950, that Orowan<sup>7</sup> pointed out that the Griffith equation represents an energy balance and, in principle, also applies to the propagation of brittle cracks in steel. He proposed a modification in which the surface energy,  $\gamma$ , is replaced by a term  $\gamma + p$ , which represents the total energy necessary for the propagation of cracks in steel. This is not only surface energy but includes  $p$ , which represents the energy required for plastic deformation during crack propagation. The term  $\gamma + p$  is therefore essentially a material property that describes the fracture toughness of a material.

With this concept in mind, it is possible to rewrite the Griffith condition for catastrophic crack propagation in the Irwin<sup>8</sup> format:

$$K_c = Y\sigma_c (\pi a)^{0.5}$$

where  $K_c$  is the fracture toughness,  $Y$  is a geometrical factor, and  $\sigma_c$  is the critical stress necessary to propagate a crack of size  $a$ . Crack size  $a$  can also be thought of as the critical size that is required before a crack can propagate in a catastrophic fashion when the applied stress is  $\sigma_c$ . It turns out that, in the case of a subcritical (or safe) crack, the term  $Y\sigma (\pi a)^{0.5}$  can be used to represent the actual stress distribution (stress intensity  $K$ ) some distance away from the crack tip. The Griffith condition for catastrophic crack propagation then requires that stress intensity  $K$  should be equal to or greater than the fracture toughness,  $K_c$ .

The concept of stress intensity has proved singularly successful in the handling of all sorts of fracture problems. In the case of stress-corrosion cracking, for example, where slow (subcritical) cracking occurs, it has been shown that the stress intensity has to reach a critical value,  $K_{ISCC}$ , for cracks to grow. This concept is more clearly shown in Figure 6, where the minimum stress required for subcritical crack growth, as well as the stress required to induce catastrophic crack propagation, is related to the crack size. Even in the case of metal fatigue, the growth of a fatigue crack per cycle ( $da/dN$ ) can be related empirically to the cyclic stress intensity ( $\Delta K$ ) by means of the Paris equation<sup>10</sup>:

$$da/dN = A(\Delta K)^n$$

where  $A$  and  $n$  are constants.

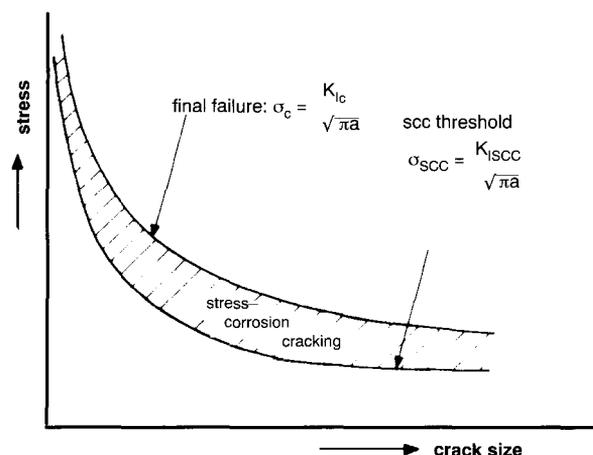


Figure 6—Relationship between stress and crack depth for stress-corrosion and catastrophic failure<sup>9</sup>

## A bird's-eye view of materials engineering

However, all has not been said and done; although much of the groundwork has been done, much remains to be explained. The challenge is to extend the principles of fracture mechanics to non-metals and composites in particular. There are, of course, many examination questions in fracture mechanics that have to be answered by students. Professor Orowan's exams were always very taxing in this respect. In many instances, students recognized so little of the classwork in the exam paper that they had to look at the heading to make quite sure they were in the right examination hall. One of his questions that I can still remember asked why cracks in glaciers never extend very deeply into the glacier. Another question asked for an explanation of why nylon shirts (which had just come onto the market) blackened in the folds at the cuffs soon after they had been worn a few times. (The disadvantage of these shirts was that, even with the best washing techniques, it was not possible to clean the areas where material was folded in creases.)

### Reflections

It is very difficult to predict the future. One's outlook for the future is, of necessity, determined by one's experience of the past. Scanning through recent topics on mechanical metallurgy in the technical literature, I often get the feeling that more and more is being written about less and less. I get the impression that many of the really major problems have been solved, and that it is the finer details of the greater painting that now need to be filled in. This, of course, is not to detract from the great importance of specific details. It is also not altogether true that all the classic problems have been solved. The whole subject of stress-corrosion cracking, for example, is still clouded and controversial.

On the whole, however, remarkable progress has been made in the unravelling of a vastly complex problem. One of the great challenges that remains is to coordinate and integrate this vast amount of information in a coherent fashion so that it can be taught to young engineers in such a way that they can apply it successfully in practice. This is one aspect where most teaching breaks down. There seem to be very few individuals who are able to apply their knowledge to the many and varied practical problems of a materials nature that are encountered in industry. In practice, engineers require highly specialized knowledge and experience, often in quite unrelated fields, to understand a problem and to arrive at the optimum solution.

Much has lately been made of the potential of new engineering ceramics in all manner of high-tech applications. In many ways, this reminds me of 35 years ago, when everybody was working on titanium. It was hailed as the new wonder metal, being light and highly corrosion-resistant, having a high melting point, and being highly resistant to oxidation. In addition, the mineral from which titanium is extracted (rutile) is fairly abundant in the earth's crust. Despite the phenomenal effort that was devoted to the development of the metal, it remained very expensive. It was also very difficult to cast, weld, or fabricate, and its creep resistance, at high temperature in particular, was very disappointing. The net result is that, although the alloy design was worked out 30 years ago, it is only recently that titanium has found application in chemical engineering, where it is used today for its

superior corrosion resistance. Much the same could happen to the new ceramics, which can be made extremely strong and hard, but are brittle and susceptible to fracture when dropped.

On the other end of the scale, composites have been hailed as a breakthrough in engineering materials in that components with quite diverse properties can be combined to produce new classes of materials. Thus, it is possible to reinforce resins with strong glass fibres, or to combine ceramics with metals, for very specific high-tech applications. There are, however, limits to this concept. One of the limitations is the environmental requirement that components should, as far as possible, be capable of recycling so as to reduce pollution. Most composites are not amenable to recycling, which is also true of many alloys. Both aluminium and steel, once contaminated with copper, cannot be purified economically. In the future, environmental issues may lead to the selection of simpler, less effective materials that can be recycled effectively.

Obviously, there is a limit to the quest for the ultimate material, and selection is usually a matter of compromise. Materials have to be thought of as non-permanent. Except for diamonds perhaps, which are 'for keeps', engineering materials are subject to all sorts of wasting such as cracking, wear, corrosion, and other forms of decrepitation, which have to be managed in a cost-effective way. Much can be learnt from biological structures, which came into being long before artificial ones. Progress in evolution was dependent upon the development of stronger biological materials. The earlier and more primitive animals were made mostly of soft material because it could extend in various ways. Soft tissue is also usually tough and able to absorb energy without fracturing. The impression one gets from Nature is that it has accepted the use of stiff material rather reluctantly. As animals became bigger and emerged from the water, most of them developed rigid skeletons with bones, teeth, and sometimes horns. Yet animals never became predominantly rigid devices like most modern machines. The trend in engineering to design very rigid structures may be under attack. More and more plastics are being used today in the manufacture of components that were previously made rigidly from metals. How far these tendencies will persist is difficult to predict, except to say that there is probably still a great deal of scope left for the replacement of metals with plastics. However, there are limits as to how far this process can be carried through.

### The road ahead

The dominant position of extractive metallurgy in South African industry, which is based on the extraction of metals and the beneficiation of minerals, goes without saying. As the economy develops, however, our materials-producing and conversion technology will become more sophisticated. In order to improve our balance of payments and to produce employment opportunities for our people, we will have to add value to our raw materials before they are exported. The result will be that materials engineers, who are intimately concerned with manufacturing processes, and with the properties and applications of the products, are going to be in greater demand. Keen international competition calls for materials engineers who will be involved in product development, quality control, process management, and marketing. This will require engineers with a broad-based education who

## A bird's-eye view of materials engineering

are fully conversant, not only with metals, but also with quite different materials such as ceramics and polymers. Apart from a strong basic approach to the mechanisms responsible for properties, the materials engineer will have to know about production processes and to understand the influence they have on material performance. Owing to the highly varied nature of materials, there is also a requirement for some detailed specialization in one or two subjects.

In the education of materials engineers and technologists, universities and technikons should complement each other rather than compete. In the development of entrepreneurial skills, in particular, the universities will have to play a leading role. In the new South Africa, there will be a massive demand for human development. Even at this early stage, it is clear that we cannot rely on State financing alone to meet our financial requirements. The need for better mentoring, bridging courses, and encouragement of our students will call for a greater commitment from the teaching staff. We will also increasingly have to focus our activities on the critical relationship between technology and our nation's economic health.

An important strategy in this regard will be to involve industry in the process. A broad-based involvement in both teaching and research aspects is envisioned. We as educators should not fear closer ties with industry or the loss of our independence. The relationship between university and industry that we had in the past is destined to change as we

search for common ground, intensified by international competition. The demand for technology transfer in much less time than previously is imperative.

Apart from offering the traditional undergraduate and postgraduate courses, the university, in collaboration with industry, should pay more attention to continued education and refresher courses. Although the theme of this Symposium has concerned materials in action, our focus in the future will have to be much more on people in action.

### References

1. ASHBY, M.F. The microstructure and design of alloys. *Proc. 3rd Int. Conf. on Strength of Metals and Alloys*. Cambridge (UK), 1978. vol. 2, p. 8.
2. GRONSKY, R. *Images of materials*. Williams, Pelton, and Gronsky (eds.). Oxford University Press, 1991. p. 236.
3. BARSOM, J.M., and ROLFE, S.T. *ASTM-STP* 446. 1970. p. 281.
4. HETENVI, M. *Handbook of experimental stress analysis*. New York, John Wiley. p. 913.
5. INGLIS, C.E. Stresses in a plate due to the presence of cracks and sharp corners. *Trans. Inst. Naval Architects*, vol. 55. 1913. p. 219.
6. GRIFFITH, A.A. The phenomenon of rupture and flow in solids. *Phil. Trans. Roy. Soc.*, London, vol. A221. 1921. p. 163.
7. OROWAN, E. *Fatigue and fracture of metals*. Cambridge (USA), M.I.T. Press, 1950. p. 139.
8. IRWIN, G.R. *Trans. ASME, J. Appl. Mech.*, vol. 24. 1957. p. 361.
9. BROEKMAN, D. *Elementary engineering fracture mechanics*. 4th edn. The Hague, Nijhoff, 1982. p. 22.
10. PARIS, P.C., GOMEZ, and ANDERSON. A rational analytical theory of fatigue. *The trend in engineering*, no. 13. 1961. p. 9. ◆

## The Mintek Aurora Programme\*

By the end of 1996, more than 700 disadvantaged students will have passed through colleges associated with the Mintek Aurora Programme (MAP). This will contribute significantly to the technologically competent workforce of South Africa and, at the same time, will have afforded many deserving youngsters the opportunity of meaningful careers.

With pressure on South African companies to reflect the demographics of society in their human-resource profiles, an in-house MAP college provides a solution to this and to other topical issues, including social responsibility and RDP obligations. A company that starts a MAP college selects a small group of disadvantaged matriculants from its local community, and gives them a chance to upgrade their maths and science symbols.

The programme took off in 1992 with eleven students, and their results on completing the year-end exams showed that all of them had increased their grades by at least two symbols. While the high-flying students progress to university studies, most of the students achieve results that qualify them for technikon bursaries.

The main differences between MAP and other programmes of educational upliftment are as follows:

- ▶ MAP students receive not only a theoretical but, more importantly, a technical education, with in-house training and familiarization with the workplace as key elements.
- ▶ They become immersed in the host company's culture, and the Western work ethic becomes ingrained.
- ▶ They also benefit from in-service and after-education mentoring.
- ▶ In most cases on completing their studies, they are assured of employment and a meaningful career.

MAP is currently supported by Denel, EMSA, Gencor, Johnson Matthey, Kentron, Iscor, LIW, Mossgas, Reunert, Sentrachem, Silverton Engineering, and Randgold.

For more information, please phone Dr Glyn Moore at Mintek on (011) 709-4271. ◆

\* Issued by Mintek, Private Bag X3015, Randburg, 2125.