NEW MATERIALS TECHNOLOGY: ANOTHER AUSTRALIAN LOST OPPORTUNITY?*

Tom Forester

Three megatechnologies will dominate the last decade of the 20th Century: Information Technology, Biotechnology and New Materials Technology. New materials have been the least well publicized, yet they play a crucial precursor role in most other technological innovation. Developments in materials science now give us the ability to design so-called 'advanced materials' from scratch for specific purposes. They have a wide variety of applications. In addition, new materials technology extends the notion of choice in the production process and as such it has major implications for engineers, designers and managers.

Australia is in theory well-placed to take advantage of the materials revolution in terms of natural resources, environment and existing research strengths. But although some impressive and useful work has been done by the Department of Science in targeting fruitful areas for future research, an international comparison of materials R&D and a review of what the Australian government and private sector has done so far suggests that Australia once again is doing too little too late.

Keywords: advanced materials, new materials technology, technology policy, research priorities

INTRODUCTION

Every five years, Japan's Science & Technology Agency surveys around 2,000 Japanese scientists for their predictions of what technological advances might be expected in the next decade or so — recurring favourites include cures for cancer, the ability to forecast earthquakes, economically-viable deep-sea mining, clarification of the ageing process, replacement of human organs, and abundant nuclear and/or solar energy. But as Hondros points out, 14 out of the 22 categories of prediction in the 1982 survey involved breakthroughs which depended crucially on a materials precursor — usually advances in ceramics, plastics, alloys or composites.[1] The 1987 survey demonstrated an even more remarkable Japanese obsession with new materials: top predictions

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for the next 20 years included the commercialization of ceramic superconductors (materials which conduct electricity without resistance), the construction of superconducting magnetic levitation trains and the widespread use of biomaterials (artificial tissues and organs which can augment or totally replace bodily ones).[2]

As long ago as 1980, the Japanese government targeted new materials technology, recognizing that it would take its place alongside information technology and biotechnology as one of three megatechnologies that would dominate in the 1990s and beyond. They realized that leadership in so-called 'Advanced Materials' — materials which begin life in the mind of the scientist in the laboratory rather than in the ground — would be the crucial enabling factor underlying leadership in many other areas of science and technology. In consequence, the Japanese Ministry of International Trade & Industry (MITI) launched a 10-year programme of research into six key areas of new materials: advanced or 'fine' ceramics; high-performance plastics; composites, especially carbon fibre composites; electrically-conductive polymers; advanced alloys; and synthetic membranes. As Gene Gregory explains,[3] the general aim of this ongoing project is to produce materials which are light but strong; functional at high temperatures; of superior electrical and magnetic properties; made from readily-available resources; and energy efficient to make and use.

Materials of one kind or another have been vitally important throughout human history. We talk of the 'Stone' Age, the 'Bronze' Age and the 'Iron' Age, implying that a material was the defining technology of an era. The invention of glass, paper and gunpowder marked further turning points in the path of human progress. The Industrial Revolution, of course, was based on new ways of processing the materials coal, iron and steel.[4] The 20th century could be deemed the Plastics Age in that plastics production increased from 1907 start to overhaul steel production in volume terms by 1979 and perhaps one day the current period might be referred to as the Age of Silicon. But the big difference between earlier centuries and today is that in the past the human race has merely adapted naturally-occurring materials and minerals for its use. Now science and technology is giving humans the ability to *design* the materials they require.

Thanks to developments in materials science, it is becoming increasingly possible to predict the properties of materials before they are even made and to modify the recipe to get the desired result to suit a particular application. These advanced materials can be designed from the molecules up — hence the increasing use of the term 'Nanotechnology' (or 'the technology of tiny things')[5] — they aren't ripped out of the ground and transported across the seas at enormous cost. This shift to 'designer materials' will thus benefit nations which are consumers of raw materials and disadvantage the traditional producer nations like Australia. The new materials technology therefore represents an entirely new way of going about things and as such it presents a major new challenge not only to managers, designers and entrepreneurs, but to governments all over the Globe.

ADVANCED MATERIALS

The new materials fall into six major categories: ceramics, plastics, composites, alloys, semiconductors and optical fibres.[6] Fine ceramics based on minerals like alumina, titania and sand are being used increasingly in engines and electronics because they are harder, lighter and stronger than many metals, they don't wear out, they don't rust and they can withstand enormous temperatures. Eventually, ceramic parts will require little or no machining. The Japanese government has put ceramics at the top of its list of 'next generation' industries. Ceramic engines already developed by the Japanese have boosted fuel efficiency by 30-40 per cent, but they are prone to crack or shatter and it is taking scientists much longer than expected to perfect ceramic materials which stand up to the stresses and strains of actual use. Even so, Nissan already sells a version of the 300 ZX sports car with a ceramic turbocharger rotor and both Isuzu and Toyota are talking about part-ceramic diesel engines within two to three years.

High-temperature superconductors — which have attracted a great deal of attention in the media over the past 18 months — are really ceramic oxides based on a variety of minerals and rare earths such as yttrium and lanthanum. A series of stunning breakthroughs, beginning with an experiment by Karl Alex Müller and Johannes Georg Bednorz at IBM's laboratory in Zurich, Switzerland, in January 1986, has greatly excited the scientific community and has set off a world-wide race to develop the first commercial room-temperature superconductors. Superconductivity holds out the prospect of a new generation of microchips and supercomputers which would be much more powerful and would never need cooling. Transmitting electricity without loss would obviously save $millions and revolutionize the energy industry. Thanks to the so-called 'Meissner-effect' — a phenomenon by which a superconductor excludes any magnetic field that comes near to it — superconductors also make possible the more economic construction of magnetic levitation trains and medical scanners. Superconductors may in addition transform science itself by enabling scientists to smash atoms more easily. This might lead to practical nuclear fission and thus cheap, inexhaustible energy supplies.[7]

High-performance plastics and composites look set to transform the auto and white goods industries. Already, many cars have plastic body parts and all-plastic cars and planes — held together by the new superglues — could be common in the next century. General Motors claims that 20 per cent of its cars and 50 per cent of its vans will have all-plastic bodies by the early 1990s. Plastics are often cheaper, lighter and stronger than metals. They can lower manufacturing costs because they use less energy, they are self-colouring, they can utilize snap-fit assembly and they can reduce a large number of parts into one moulding. In addition, they don't rust and they don't dent so easily. Since they are entirely artificial, plastics can be made to have thermal or electrical insulation properties, and /or be designed to decrease noise, vibration, friction and/or wear. Their disadvantages include high initial investment costs, an inability to withstand heat or certain chemicals and the finish on plastic parts is often not as good as that on metals. Despite the problem with heat, a US company and a Canadian company have both recently demonstrated working plastic car engines.[8]

Advanced composites — fibres of metals or ceramics embedded in plastic — promise to revolutionize the aerospace industry. The older-type carbon fibre (as found in tennis racquets) has been used for a long time for aircraft parts, but it is now possible to construct entire wings, tails and even whole airframes using the new composites. Thirty per cent of the airframe of the AV-8B *Harrier* jump-jet is made of composites and such materials were behind the recent successes with human-powered flight and the non stop round-the-World trip by the *Voyager* craft in 1987. Lightweight turboprop aircraft made entirely from compositie̐s could become common in the late 1990s.

New metal alloys which are lighter, stronger and easier to use than conventional metals will have a major impact right across the range of manufacturing industries. Some are made utilizing powder metallurgy — the forming of parts by pressing and heating metallic powders in molds (thus reducing the amount of machining required) — while others are created through rapid solidification or quenching. This process rearranges the atoms during cooling to create alloys which are much stronger than conventional metals and they also have a much lower resistance to electricity. For example, *Sun Raycer,* the solar-powered car from General Motors which easily won the 1987 solar car race across Australia, has a so-called Magnaquench electric motor made in this way. Being constructed of stronger material means that it is lighter, smaller and therefore more efficient than other motors. Other techniques for handling the new alloys include superplastic forming, direct sheet casting and squeeze casting.

New materials lie behind past, present and future advances in semiconductor technology, the very foundation of the computer revolution. Transistors, integrated circuits and the chip itself only came about after materials scientists learned how to process silicon from common sand. Now new materials processes such as plasma etching, ion implantation and molecular beam epitaxy are being used to further miniaturize chip circuitry and entirely new materials like gallium arsenide are being deployed to create chips which are faster, use less power, and are more radiation and temperature resistant than silicon chips. In addition, new types of semiconductors such as charge-coupled devices, wafer-scale chips and superlattices are being developed with the aid of new materials.

In the related sphere of photonics — in which light pulses (representing information) are generated by lasers and transmitted by fibre optic cables — advances in materials technology are transforming telecommunications and promising to make optical computing a reality. Optical fibres are tiny strands of pure glass no wider than a human hair that can carry thousands of telephone conversations or other digitized data in the form of extremely fast streams of light pulses. They are smaller and yet have a much higher capacity than conventional copper cable, they are faster, easier to maintain, easier to handle and they are getting cheaper. Optical fibre is rapidly becoming the preferred medium for transmitting voice and data over long distances.

Finally, mention should be made of the new generations of high-tech cements and superglues. The new cements — made by blending traditional cement with metals, plastics and ceramics — are being developed for use in everything from concrete brake shoes to cement armour-plating for tanks. So-called 'macro-defect-free' (MDF) cement is unusually strong, stiff, soundproof, resistant to chemicals and is able to be machined like metal. The new high-performance toughened adhesives or superglues can be used for joining plastics, metals and ceramics. In manufacturing industry, superglues may one day replace spot-welding as the main method of bonding. This will clearly have major implications for production processes.

NEW MATERIALS TECHNOLOGY

New materials technology extends the range of *choice* in the selection of materials for a given product or production process. Two decades ago, Alexander[9] pointed out that advancing materials research meant that quite different materials could now be used for the same purpose. Production decisions in future would require subtle choices to be made involving trade-offs between technology and economics. Writing even earlier, Meier[10] argued that *substitutability* would increase as the stock of knowledge about different materials and materials processes (and the flow of communication about them) increased. Meier was perhaps the first to make the link between developments in information technology and information processing with developments in materials science. Indeed, in a remarkably perceptive commentary on Meier, Fisher correctly predicted the coming of nanotechnology as materials science increases our knowledge of materials and our ability to design new materials for specific industrial and consumer uses. He even foresaw the integration of computers into the production process, not only in the form of automation but for use in the *selection* of materials.[11]

More recently, Clark and Flemings have shown how planning the production of a car these days involves complex computations of the relative merits of particular materials and production processes.[12] This means trade-offs between cost, weight, ease of production, even production-run planned (tooling costs) and component-integration (reducing the number of parts). For example, a plastic bumper may have superior qualities to a metal bumper and be cheaper to produce up to 50,000 units, but after that the dies have to be changed — this makes metal with its once-and-for-all tooling costs a better choice for longer production runs of, say, 200,000 units.

The driving forces behind materials innovation in the auto industry have been growing international competition, the oil price shock of 1973 and new regulations in the US governing fuel economy, safety and exhaust emissions. This resulted in a frantic drive to boost fuel efficiency by the reduction of vehicle weight, while changing consumer preferences in durability (reduced corrosion), performance (improved aerodynamics) and style have created a further wave of materials innovation in the auto industry. The combined impact of these forces has been to dramatically change the materials content of cars and to initiate a total reexamination of the process by which cars are designed, developed and manufactured using computers as an analytical tool. Information technology and new materials technology now meet in the production process.

In the aerospace industry, a similar combination of forces has been at work. The desire to reduce the weight of aircraft in order to boost fuel economy has been paramount, but manufacturers have also been keen to cut fabrication costs in order to remain competitive. The reduction of engine noise in order to conform to government regulations has become a top priority as community groups have succeeded in getting noise restrictions imposed on urban airports. Governments have also set successive objectives for the performance of aircraft, satellites and missiles. In 1986, the Reagan administration in the US set goals for subsonic, supersonic and hypersonic flight (hypersonic vehicles like the planned aerospace plane are expected to fly from London to Sydney in 2 hours). In order to meet these goals, further advances in materials technology will be necessary to achieve further savings of fuel and weight and to cope with the very high and very low temperatures experienced in transatmospheric flight.

Every aspect of production and distribution in the energy industry involves the use of appropriate materials — for example, materials which conduct electricity and materials which resist heat or corrosion. In fact, materials are becoming more important in energy production because energy is being generated in more complex ways such as solar power, nuclear fission and coal liquefaction. Advanced materials can reduce transmission losses, friction losses and improve the safety and reliability of energy production. Likewise, the field of medicine is witnessing a revolution in so-called 'biomaterials' — artificial tissues and organs which can prolong life and relieve suffering. Special ceramics, polyurethane plastics, alloys, glasses and composites are being used to make bone implants, replacement joints, artificial arteries, synthetic blood and entirely artificial hearts. Replacement tendons, ligaments and even skin are being developed.

WIDER IMPLICATIONS OF THE MATERIALS REVOLUTION

Innovation in materials to a great extent determines the pace of technological advance in many key industries — especially the computer industry — which in turn greatly influences productivity, capital formation, the demand for labour and the overall rate of economic growth. Our standard of living today has been largely determined by past discoveries of 'new' materials and our future prosperity will in large part depend on the fruits of contemporary research into today's 'advanced' materials.

One consequence of the rapid progress being made in materials science is that demand for traditional raw materials — including those of strategic importance — is falling, or at least not keeping pace with economic growth. Contrary to what was being predicted 15 years ago by the Club of Rome and the *Limits to Growth* school of thought, the world today as a whole has a large surplus of food and raw materials. OECD (Organisation for Economic Cooperation and Development) figures also show that the prices of agricultural products and metals in late 1987 were at their lowest in real terms for more than 30 years. The OECD argues that technological change is the biggest single factor behind falling prices, because it has both expanded supply by improving productivity and reduced demand by making cheaper substitutes available. Advances in new materials technology were apparently unforeseen by the Malthusians of the early 1970s. Indeed, history shows that predicted materials shortages rarely materialize because substitutes and new ways of processing materials are invariably developed.[13]

In a wide-ranging paper,[14] Larson *et al.* go further and argue that the industrial nations are witnessing a fundamental and probably irreversible historic shift from a Materials Age characterized by low-tech products with a high materials content to an Information Age characterized by high-tech products with a low materials content. Identifying a 'cycle' in the demand for materials, they say that four factors are responsible for the declining consumption of traditional materials: the substitution of one material for another, which has slowed the growth of demand for particular materials; design changes in products which have increased the efficiency of materials use; the saturation of traditional markets that expanded rapidly during the Era of Materials; and the growth of new markets which tend to involve products that have a low materials content. This 'profound shift' from traditional materials to advanced materials will inevitably mean a further shift in wealth and power away from traditional producer nations in favour of the advanced industrial nations. The message for Australia is obvious.

GOVERNMENT SUPPORT FOR MATERIALS RESEARCH

Governments all over the world are taking steps to boost research into new materials, but as we saw above it is Japan that boasts the most coherent materials research programme. According to DITAC, the Japanese are spending about A$548 million in the ten-year period, 1981-90.[15] Dr. W.J.McG. Tegart, then Secretary at the Department of Science, confirmed that "it is Japan that now sets the research agenda for the industries of the advanced world."[16] However, public and private sector expenditure on new materials R&D is likely to be much higher in the US, although the exact total is hard to determine. Some 14 Materials Research Laboratories which receive US$24 million annually are established centres of excellence and both the US Department of Defense and NASA are responsible for massive spending on materials R&D. Successive reports to the US government have highlighted the dangers of falling behind Japan. In Europe, the EC in 1986 launched the European Research on Advanced Materials (EURAM) programme. France (public funding alone about A$150 million per annum) and West Germany (about A$130 million) are moderate spenders on materials R&D, while the UK, Sweden and Canada are minor players.[17]

The discovery of high-temperature superconductors has created a further wave of interest in new materials, with the US and Japan leading the way with new R&D programmes. The US government kicked off with US$1.6 million for universities and quickly followed-up with a US$150 million superconductor initiative funded by the Department of Defense. In Japan, MITI boosted superconductor research from US$5 million to US$40 million a year, while Japanese corporate efforts have focused on the early commercialization of ceramic superconductors. In the UK, France, West Germany and Canada there were similar moves to jump on the superconductivity bandwagon.

In Australia, new materials technology was declared a generic technology by the Minister for Industry, Technology and Commerce, Sen. John Button, in 1986 — that is, about six years after the Japanese had done the same. New materials had somewhat belatedly been identified by the Department of Science as being a key technology for Australia in 1985[18] — which is pretty remarkable considering that Australia has vast natural resources of mineral sands, metallic ores and rare earths — including, for example, 70 per cent of the world's known deposits of zirconia (a vital ingredient of fine ceramics). Even more amazing is the fact that Australia has 50 per cent of the world's supply of yttrium, the rare-earth oxide that has figured prominently as a major ingredient in most of the high-temperature superconductors developed in the world so far (although the government cannot be blamed for not spotting this earlier). Australia also has, of course, an abundance of marine environments and of solar radiation.

In any event, it was proposed that Australia should develop a materials research capability, both for the application of new materials in existing industries and the development of new industries based on Australian R&D in advanced materials. It was pointed out that Australia had held — and lost — a lead in titanium alloys back in the 1950s. Today, Australia has existing strengths in zirconia and bauxite processing and these ought to be built upon.[19]

TARGETING MATERIALS R&D RESOURCES

But it is one thing to identify broad generic technologies. It is another to identify those areas where scarce R&D resources should be targeted. As has been pointed out on numerous occasions, R&D spending by Australian firms is low by international standards and is falling. In the public sector, Australia has a fragmented R&D base, with small groups working in isolation with limited facilities. Tegart points out that the existing Australian materials research effort is "scattered over at least five different divisions of CSIRO, the AAEC, Telecom, DSTO, universities and industry. Clearly, this must be an inefficient use of limited resources."[20] Moreover, these efforts are not coordinated in any meaningful way and much of the work is not perceived by industry to be relevant to its needs.

In June, 1987, DITAC published its *Selecting Technologies for the Future: A Discussion Paper.* This important document reviews recent overseas experiences with technology selection, discusses possible criteria for selection and considers candidates for Australia in the context of the industrial policies being pursued by DITAC. The authors ask many questions but the major thrust of the paper is that Australia as a nation should identify those areas of generic technology for "special attention." Such areas should have the potential to develop marketable products, processes or services within a time frame of 10-20 years. In the case of materials, the paper argues that existing R&D themes are too broad and duplicate those of other nations who are already far advanced. Instead, Australia should carefully target areas where it has a demonstrated comparative advantage and where it can benefit from plentiful local supplies of raw materials such as precious metals and rare earths.[21]

But as Johns argues in this issue of *Prometheus,* even this is not enough. While establishing the case for high technology R&D and for government intervention, he warns that studies of revealed comparative advantage and the relative abundance of different resources may only be useful in identifying broad generic technologies in which Australia might specialise. He writes: ". . . the evidence shows the results of these studies should be approached with caution. They can provide a broad indication of the directions in which R&D effort might be concentrated. In the end, however, there is no substitute for an attempt to evaluate the prospective profitability of specific individual R&D projects."[22] This, of course, begs a number of questions, such as *who* is in a position to do such an evaluation — firms aiming to commercialize the fruits of R&D would seem a good bet (for more on this, see below) — and indeed Johns does emphasize the importance of having downstream mechanisms in place.

WHAT AUSTRALIA IS — AND ISN'T — DOING

Despite these qualms, some impressive work has been going on in the area of new materials, thanks to the efforts of the Department of Science. In late 1985, the Department sponsored two two-day workshops on materials research which brought together practically all the leading figures in the area in Australia from both the public and the private sector, from the worlds of research and from manufacturing. The resulting report talks of "Australia's alarming mediocrity in the world's advanced materials race" and charges that Australia's existing materials research effort "has not been playing an adequate role in helping to improve existing industries or facilitate the establishment of new industries. Our resources are fragmented and this, together with the traditional freedom of researchers, has led to far too wide a range of topics being studied."[23]

The report details the deliberations of the workshops which looked at new materials and processes under the four headings of metals, polymers, ceramics and advanced processes. In each case, the brief for the participants was to seek to identify specific areas which Australia might target in the light of trends in the industry and with reference to what other countries were doing. Sensibly, the point was repeatedly made that duplicating research or targeting areas in which other nations already held a large lead would be a waste of resources and participants should also be mindful of potential markets for actual products. Each workshop was therefore asked to pinpoint those specific areas of materials research which could lead to realistic commercial opportunties for Australia and to recommend actions to bring about the research necessary to encourage commercialization in these areas.

The workshops came up with a list of "Materials Target Areas" ranging from metal surfaces and their treatment, improved metal extraction processes, opto-electronic devices, rare earths and polymers for hostile environments to biomaterials and devices, zirconia-toughened ceramics, unorthodox ceramics processing, sensors and materials property databases. The list does not closely follow areas targeted by other countries, nor is it a list of trendy subjects. It is, however, a list of areas which is believed to minimize Australia's disadvantages and maximize Australia's advantages in terms of ongoing research, existing industrial base and general environment. The target areas identified also demonstrate the inter-relationships that exist between various materials and materials processes. Such targeting could therefore help unify the whole materials research effort and the resulting synergism might magnify its effectiveness.[24] A new industry-biased body (AMRAC or Australian Materials Research Advisory Committee) was also proposed, whose job it would be to enforce the agreed targeting, chiefly by providing 'seed money' to support only collaborative research efforts in the target areas.

The first fruits of this landmark report came on 17 December 1987, when the Industry Research & Development Board of DITAC announced that grants worth a total of $4.6 million had been awarded to eight consortia planning new materials technology research projects in the target areas and in the area of high-temperature superconductivity. Interestingly, each successful application is a collaborative venture between the research sector and the commercial sector. For example, a project to investigate the feasibility of superconducting power transmission lines worth $664,000 is being undertaken by Monash University and the CSIRO Division of Materials Science in collaboration with Olex Cables Ltd. and the State Electricity Commission of Victoria. Likewise, the projects to investigate biosensors, metal surfaces, polymers for hostile environments and metal extraction processes all involve at least one industry participant. There has been no direct attempt to assess the profitability of these R&D projects, but at least they are in the target areas and the existence of commercial collaborators implies that the downstream mechanisms are in place — which may go some way to assuage the fears of Johns.

But the fact remains that the total sum of money involved in these projects is peanuts by world standards. And such jam that there is is spread exceedingly thin. For example, three of the chosen eight involve the search for high-temperature superconductivity, but three projects totalling less than $1.5 million is a drop in the ocean compared with the spending of other nations and there has been no real effort to adopt an integrated approach similar to that favoured by the Japanese. As Dr. Peter Robinson, group general manager of MML, one of the participating companies, put it: "We have the talent and resources, but in traditional Australian-style our research effort is very fragmented."[25] Or as Dr. John Collins, assistant chief of the CSIRO Division of Applied Sciences says: "Australian research is spread across the entire continent and is spread across several disciplines."[26] There is no one centre to act as a focus for Australia's superconductivity effort — and this in a nation which holds 50 per cent of the world's supply of yttrium. The discovery of high-temperature superconductivity and the revolution in advanced materials are a heaven-sent opportunity for Australia, but to date, it seems, Australia has done too little too late.

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