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EMERGING TECHNOLOGY SERIES

ADVANCED MATERIALS TECHNOLOGY 2

New, Advanced and Improved Traditional Materials and Processes

Prepared for UNIDO by Lakis C. Kaounides, City University Business School, London, United Kingdom.

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SCOPE AND DESCRIPTION

ADVANCED MATERIALS TECHNOLOGY, within the scope of the **EMERGING TECHNOLOGY SERIES**, is published in response to recent technical changes across virtually all of today's high technology fields, posed by the arrival of a generic and enabling technology, namely advanced materials and its accelerating assimilation and deployent. The materials sector has emerged as a science-based, knowledge-intensive high technology area with serious repercussions for technical change, competitiveness, growth, employment, trade patterns, location of manufacturing activities and the global division of labour. Technical change across virtually all present day high technology fields depends critically on advances in materials. Moreover, new materials development is an essential part of attempts to resolve the pressing environmental problems in mining, metallurgy, manufacturing and the global eco-system. The mastery and control of advanced materials technologies will lead to dominance in several high technology fields and major segments of manufacturing into the next century.

ADVANCED MATERIALS TECHNOLOGY is focused on the interest of policy makers in government departments, senior managers in industry and scientists who deal with materials issues, and will assist them to identify the functions new and advanced materials have in industrial and economic comptetitiveness, and in formulating their strategies for the materials sector in their countries' industries.

ADVANCED MATERIALS TECHNOLOGY aims at encouraging the development of strategic orientation and business strategies in basic materials producing industries by providing a broad interdisciplinary platform for the presentation of new materials research, development and processing concepts and their increasing role in technological leadership and competitiveness.

ADVANCED MATERIALS TECHNOLOGY aims at covering the multidisciplinary nature of materials science and engineering and its transsectoral impact on major manufacturing industries in both developing and industrialized countries.

TOPICS COVERED

Issue No. 1 covered the subject of advanced materials in high technology and world class manufacturing

- Future issues will include:
- Technical change in the 1990s and its dependence on materials science and engineering
- Science, technology and industrial competitiveness
- Industrial and technology policy
- Materials processing and manufacturing engineering

(v), 90p
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PREFACE

In the 1990s, the world's economy is being increasingly driven by the development and application of three major generic technology families, namely: new materials, biotechnology and microelectronics. The technological impact of new materials on industry will be very significant. Because of their central importance for the future development of impending new products in many industrial sub-sectors, materials and related processing technologies are internationally considered to be at the core of the product and process innovation efforts geared to provide an international competitive edge to enterprises in these sub-sectors. Spill-over effects on virtually all industrial sectors will result from the application of new materials technologies.

In future, new materials will continue to play an essential role in the development of advanced technologies in such vital sectors as energy, electronics, transportation, aerospace, telecommunication, etc. This is a more important point than the market size of new materials itself. Worldwide demand for new materials production has been increasing rapidly within the last decade and it is expected to reach US$ 100 billion by the year 2000.

For the year 2000 and beyond, new materials engineering is, from amongst the key technologies, the one with the greatest degree of interlinkage to other engineering fields and the one with the highest degree of positive external effects; for example, energy, transportation, housing, health, etc. The paradigm for materials competitiveness is that the synthesis of new materials must be integrally linked to the design and processing of the corresponding final products, since the materials are only basic components of complex systems, and as such are critical to their performance. Thus, improvements in materials quality and price have dramatic effects on the international competitiveness of developing nations' enterprises across all sub-sectors.

Priority applications are expected to focus on the following systems:

- energy engineering
- transportation systems
- information and communications systems
- microelectronic systems
- optoelectronic systems
- medical engineering

Innovations in engineering materials have also created major technological advances in recent years and the trends are set to continue into the next century. The most important impetus for new materials comes from the large multinational companies in the industrialized countries. Analysis of industrial materials research in these countries demonstrates that 33 of the 50 companies with the greatest turnover attach high, if not the highest importance to materials research, and view this area as a focus of their R&D investments. These companies have made a lasting impression on the international development and use of new materials, but definately with a focus to improving their international competitiveness through technological advances in the new materials area.

Naturally, the individual, specific R&D plans and projects of these firms are focused respectively on strategic corporate goals. On the whole, however, the research turned up a clear tendency to create cooperative research activities and combinations for the purpose of economizing on resources and increasing efficiency.

This publication will provide readers with the origins, characteristics and consequences of the revolution in materials science and engineering that took place in the 1980s. It will examine the manifold aspects of materials structure, composition, phenomena, characterization, synthesis, processing and fabrication techniques. Materials science and engineering is now multi-disciplinary in its nature, and requires inputs from solid state physics, chemistry, metallurgy, ceramics, composites, surface and interface sciences, mathematics, computer science, metrology and engineering.

We would appreciate receiving your comments on this publication and will continue our study on the transsectoral impact of materials science and engineering in subsequent issues.

Investment and Technology Promotion Division
United Nations Industrial Development Organization

CONTENTS

NEW, ADVANCED AND IMPROVED TRADITIONAL MATERIALS AND PROCESSES

ORIGINS, CHARACTERISTICS AND CONSEQUENCES OF THE REVOLUTION IN MATERIALS SCIENCE AND ENGINEERING IN THE 1980s

The insights offered by quantum physics in the early part of this century greatly enhanced our understanding of the interconnections between the structure and properties of matter. In the following decades the analysis, synthesis and processing of materials has been benefitting from the incorporation of more fundamental scientific understanding, leading to advanced materials entering atomic energy production, electronics and space programmes, amongst others. Nevertheless, such enhanced theoretical insights could only offer qualitative guidelines to modelling and prediction.

It was only very recently that quantum insights could be taken fuller advantage of. Since the beginning of the 1980s a proliferation of powerful new instruments (see Figure 1), such as the tunnel scanning electron microscope, can provide scientists with in-depth insights into the electronic, atomic and molecular structures of materials. Moreover, the exponential increase in computer power, through the use of high-speed super-computers, has enabled scientists to develop mathematical models of very complex physical phenomena which defied calculation even a few years ago. There has therefore been a quantum leap in understanding the processing-microstructure-performance relations and the physical, chemical and mechanical behaviour of both monolithic and composite materials. Using advanced computer aided instrumentation, mathematical modelling and experimental techniques, materials scientists are now beginning to offer quantitative characterisation of microstructures, thus describing the structure of a material as it evolves during processing, and its relation to resulting properties. Work is already underway, albeit at an initial stage, of extending quantitative characterisation of materials behaviour at the level of interaction between large groups of atoms and electrons using the laws of quantum and statistical mechanics, and incorporating it into materials design.

Modern materials science and engineering (MSE)[1] has emerged from its diverse scientific roots in condensed-matter physics, solid-state chemistry and synthetic chemistry, combined with practical engineering and manufacturing experience and industrial R&D laboratory research, to offer a comprehensive approach to materials. At centre stage is the close interaction and close relationship between the structure/composition, properties performance in use, and the synthesis/processing path of a material (see Figure 2). This approach is now both necessary and applicable across all classes of materials, thus rendering all other empirical and craft-related approaches to materials development obsolete. Improvements in existing materials and the introduction of new materials is thus predicated on the methods and tools of a modern MSE in possession of a strong component in pure science, coupled with a comprehensive processing, fabrication and engineering base. Given the permeation of modern MSE across all classes of materials, there is a sense in which all materials are becoming "new" materials. By the late 1980s, materials science and applied research achieved such greatly enhanced capabilities for manipulating and building materials inconceivable at the beginning to the decade. For example, at the atomic level:

> "....instruments such as the scanning tunnelling microscope and the atomic resolution transmission electron microscope can reveal, with atom-by-atom resolution, the structures of materials. Ion Beam, Molecular Beam, and other types of equipment can build structures, atom layer by atom layer. Instruments can monitor processes in materials on time scales so short that the various stages in atomic rearrangements and chemical reactions can be distinguished. Computers are becoming powerful enough to allow predictions of structures of time-dependent processes, starting with nothing more than the atomic numbers of the constituents." (Source: US National Research Council, 1989, p.74)

The 1980s: mastery over matter

It is this, almost incredible, and accelerating, ability of materials scientists to intervene at the electronic, atomic, molecular and macrostructure levels, to quantitatively characterise, model, predict and control the structure evolution along the processing path, and to manipulate and enhance properties in order to achieve desired industrial and military applications, that lies at the core of the materials revolution. It is responsible for the great improvements in the properties and processing technologies of existing traditional materials and the proliferation of knowledge-intensive, high-performance materials, such as advanced ceramics, engineering polymers, advanced metals and ceramic-, metal- and polymer-matrix composite systems (see Figure 4). Although the 1960s and 1970s did witness the introduction of important new materials, which could be viewed as advanced materials, we wish to focus upon the development of the 1980s as marking a structural break in the mode of development and utilisation of materials in industrial systems. The revolution in MSE and its exponential ability to understand the forms and behaviour of matter, predict, create new forms and control its form and uses, is leading to massive transformations in both materials producing and using firms and industries. Below we examine the imperatives ushered in by the ever expanding pure and applied materials scientific frontier, and the consequences of this for strategic responses and reorganisation of firms and industries internally, domestically and globally.

The development of advanced high-resolution analytical technologies has provided materials scientists with a repertoire of tools with which to probe the intrinsic electronic structure of all materials.

This has led ultimately to an improved understanding of the fundamental nature of the "solid state".

High-voltage electron microscopy
Scanning electron microscopy
X-ray diffraction
Excitation spectroscopy

Electronic level
↓
Atomic level
↓
Molecular level
↓
Grains
↓
Macroscopic level

Fig. 1: New analytical technologies

New Processing technologies enable scientists to alter the structure and, ultimately, the performance of materials.

Such advances have enabled material scientist to improve existing materials as well as to create new manmade "engineered materials" with properties tailored to meet the special needs of the end user.

Rapid solidification
Vapor phase deposition
Ion implantation
Molecular beam epitaxy

Structure
↓
Properties
↓
Performance

Fig. 2: New materials processing technologies

Source: L. Sousa: *Problems and Opportunities in Metals and Materials*, US Bureau of Mines, 1988.

The multi-disciplinary nature of modern MSE

The need to examine the manifold aspects of materials structure, composition, phenomena, characterisation, synthesis, processing and fabrication techniques, involves the integration and interaction of many hitherto specialised fields and disciplines, increasingly pooled in synergistic collaboration. Materials science is now a multi-disciplinary science requiring inputs from solid state physics, chemistry, metallurgy, ceramics, composites, surface and interface sciences, mathematics, computer science, metrology and engineering. In fact, rigid separation of the different disciplines is becoming inappropriate and barriers or boundaries between them are beginning to erode.

The trend in modern science towards an examination of elementary particles, atoms and molecules cuts across materials whatever their origin, and indeed crosses over and embraces other fields such as biotechnologies and genetic engineering of living organisms. Indeed, recent evidence points to a merging of life sciences (molecular biology) and chemical science and polymeric materials. New developments have facilitated the micro-electronics revolution. In turn, developments in microelectronics have repeatedly given added impetus to chemistry via, for example, computer-aided molecular design and efficient search for new active substances, or microprocessor control of manufacturing process. And new discoveries in physics and biology greatly expand the fields open to chemistry. Hence breadth of knowledge and synergistic collaboration is now a fundamental and inescapable need for the conduct of basic research. In any case, what is clear at this stage is that the nature and complexity of the problems in materials synthesis and processing is such that a joint simultaneous team effort across many disciplines, several professional staff and previously isolated research teams is now definitely required. Multi-disciplinary materials design, product development and processing capabilities are therefore becoming crucial at the level of the firm, the industry, the university, the research laboratory, or the economy, for that matter.

The importance of synthesis and processing

Materials research and development now require that materials scientists become closely involved in the processing and fabrication stages of production. The micro-structure of materials, that is the arrangement of atoms into crystalline arrays or disordered structures, determines properties and performance, but the mechanism that links all of them is processing. The controlled processing path a material follows will affect microstructure and thereby properties and performance in use. Another aspect to this is that whereas in the past processing techniques were largely non-scientific and empirically based, now the science content of not only the material but, significantly, also of materials processing technology in both traditional and new advanced materials has increased by a quantum leap.

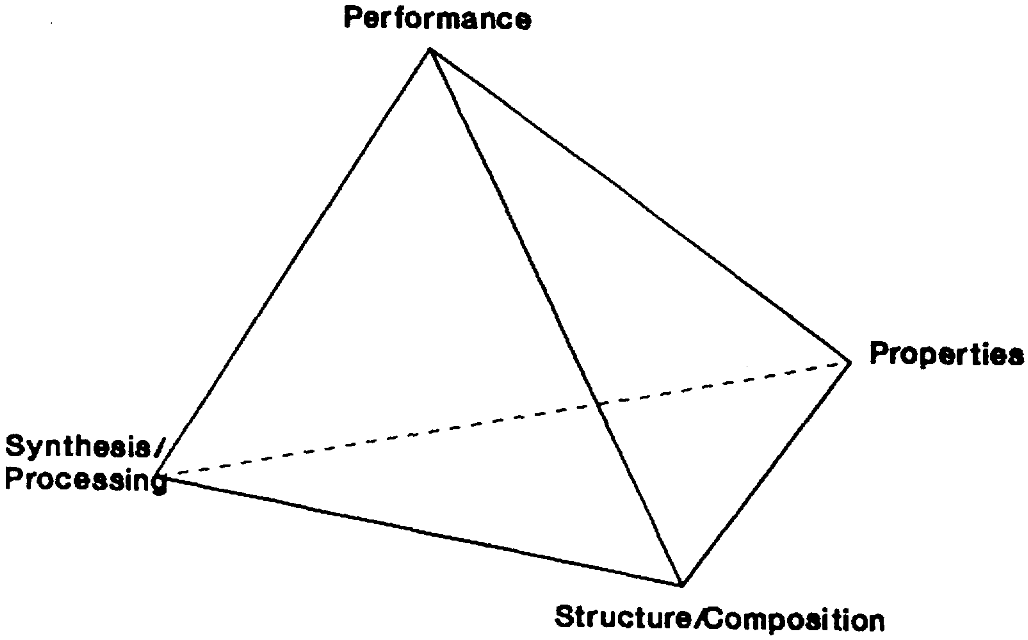


Fig. 3: The four elements of materials science and engineering

Source: *Materials Science and Engineering for the 1990s*, National Research Council Committee on Material Science and Engineering, 1988, p.29.

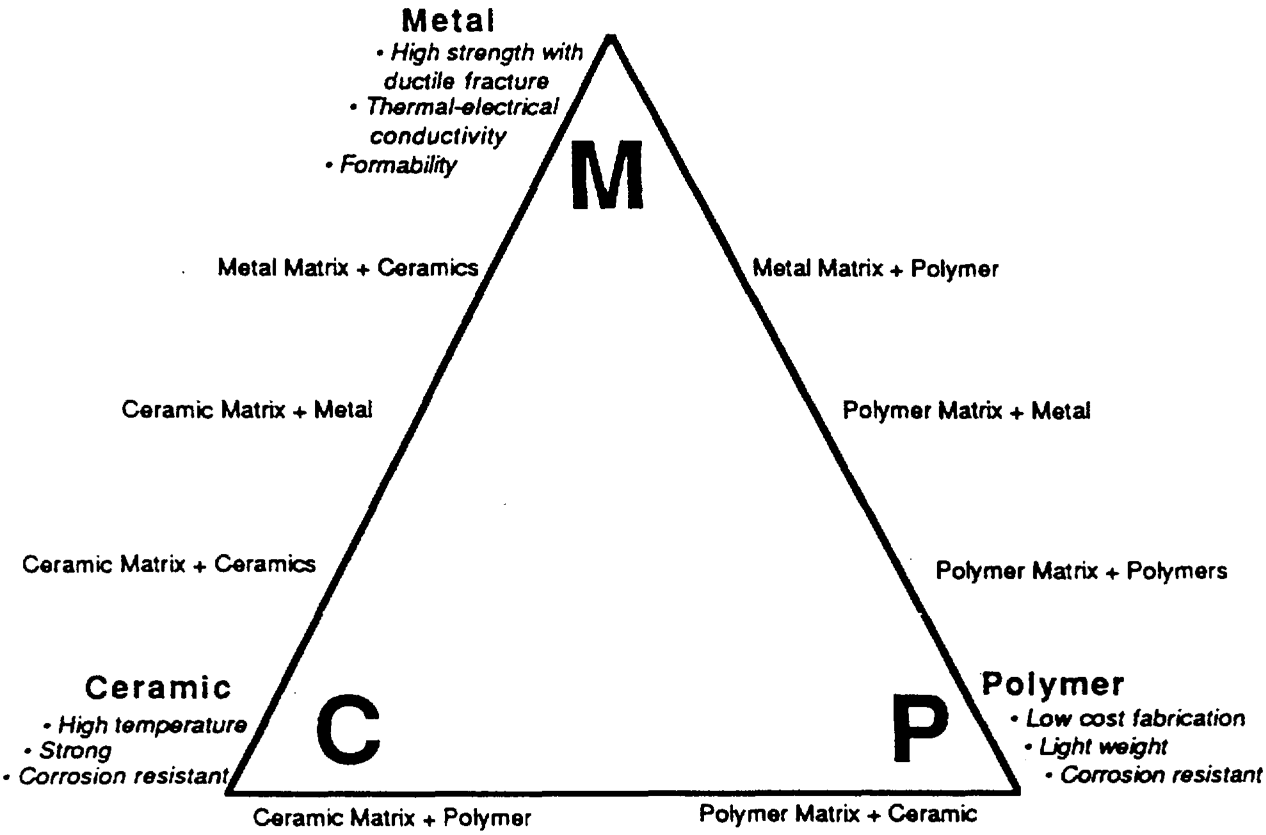


Fig. 4: Advanced material systems

Source: Alcoa, Position Paper from the 10th Biiennial Conference on National Materials Policy.

Science into processing

Materials scientists, across the whole spectrum of disciplines and specialisations, are therefore becoming increasingly involved in the processing and fabrication stages of materials development. Conversely, materials engineers need to be closely attuned to the scientific and theoretical aspects of materials design and modelling. This has made for a close integration of the subject matter of materials science and engineering in terms of its pure and applied aspects viewed by necessity as a coherent whole. At the same time this has led to a fruitful feedback and cross-fertilisation between scientific understanding and the engineering problem of processing materials, such as to control structure and improve performance, reliability and reproducibility at low cost. The infusion of science into processing has led to several new processing technologies, without which new materials would have remained curiosities and existing materials would not have registered the tremendous improvements in properties, performance and cost that they have recently displayed. Such new processing technologies (see Figure 2) are being developed through the use of computer controls, sensors, process modelling, artificial intelligence, standards, in process non-destructive testing, etc. We discuss this further below.

Improving the properties of existing materials, or creating entirely new materials, is next to useless without the development of the necessary processing technologies in each case, and the equipment and machinery to manufacture the components, shapes and sub-assemblies entering complex engineering systems and final assembly. It is the case, of course, that processing is a major constraint in the commercialisation and practical application of the high temperature superconductors, photonic and opto-electronic materials, biochips and many materials engineered at the molecular level. In metallic materials, the insights of MSE have been utilised to offer dramatic improvements in properties, performance and processing costs in a new generation of high-performance metals and metal-matrix composites as compared to commodity metals a decade ago. New processing methods[2], such as rapid solidification processing, hot-and-cold isostatic pressing, electron beam processing, superplastic forming, metal injection moulding and many others, are leading to great improvements in the performance of metals. At the same time, intermetallic alloys, magnetic alloys, electronic alloys, new superalloys, high-strength steels, light metal alloys (e.g. aluminium-lithium) and metal matrix composites and laminated systems, are offering dramatic improvements in performance, costs and manufacturability, thus both fending off competition from ceramics and polymers while opening up new uses for metals.

Synthesis

Underlying the discovery of new materials with properties and exhibiting new phenomena (e.g. the high-temperature super-conductors in 1987), the improvements in the control of structure, composition and hence, properties of known materials, and progress in the development of materials processing and manufacturing technologies, lies synthesis. Synthetic capabilities in the chemical and physical combination of atoms and molecules to form materials and, its coupling to characterisation and analysis of properties, processing and manufacture is emerging as a crucial determinant of progress in pure materials research, rapidity of translating basic research to commercial application and the rate of technological change across national industrial branches and economies. Although the synthesis element of MSE necessarily retains a large scientific base, it is nevertheless, organically connected to the processing and manufacture of solid materials. For, not only does the choice of synthetic reactions, as in the preparation of high purity powders for advanced ceramics fabrication, influence subsequent processing paths, but also modern fabrication technologies involve the merging of the synthesis and processing stage into a simultaneous process, as in injection moulding of plastics. Thus, materials synthesis, processing, fabrication and manufacturing are merging in response to both forces internal to MSE, and to pressures emanating from the evolution of new production technologies, as well as the ever increasing need to transmit, fast and efficiently, materials pure research into industrial and military application.

At present, a major constraint in the diffusion of advanced materials into a wide range of technologies and industrial application is the ability to process raw or synthesized substances into reliable, high-volume, low cost useful forms, such as films, wire, components, devices and structures entering complex engineering systems. This is no more evident than in advanced structural ceramics, composites and the new high-temperature superconductors. But more than this, it is becoming clear the technological competence in materials processing and fabrication is the critical component in international competitiveness of national industrial structures and industrial branches engaged in traditional and high-technology activities. Such processing capabilities facilitate more rapid translation of research results to commercial applications, and the generation of higher quality, more reliable, low-cost products of innovative design in a wide range of increasingly sophisticated manufacturing industries. This is evident from Japanese and, to a lesser extent, south Korean experience, where manufacturing capabilities and associated materials processing technologies have been developed in parallel, to great advantage in terms of innovation and global competitive advantage.

The integration of scientific, engineering, manufacturing and marketing capabilities

In addition to the vastly enhanced scientific and knowledge content as well as interdisciplinary efforts required in materials development and production (and use) in the 1990s, further serious implications follow.

Simultaneous materials, manufacturing and product design

Engineering and materials science divisions have now been eradicated with a resulting two way interaction and integration. Moreover, it is now becoming necessary to integrate materials science with manufacturing, product design and performance, as a simultaneous process. This is to be contrasted to the sequential and disconnected product and process development path hitherto followed in materials industries. For example, in metals, the product development process followed the sequence of new alloy creation by the alloy technologist, who then handed it to the ingot caster, who then passed it to the fabricating technologist and then, finally, it reached the product designer after an average wait of seven years! This serial, lengthy one way process of material development and production is out of date in today's market place and competitive environment requiring the creation, testing and application of complex new materials technologies in record times. It is not simply a question of speeding up the R&D and innovation cycle. Rather, the new conditions in materials science necessitate a simultaneous two way approach (see Figure 5) to materials research, advanced manufacturing techniques, product design, performance and marketing, including a crucial way, a close interaction and integration with end users. The scientific and engineering capabilities of the materials producers need to be in close touch with the performance requirements and engineering and manufacturing processes employed by the end user industry, e.g. automobile or aerospace. Although new materials development has to a large extent been demand driven, generalised application would and does require that end users be educated as to the properties and quality reliability of a new material.

The integration of materials producer and end-user design and manufacturing procedures

In short, what is emerging is not only a breakdown of a firm's traditional internal divisions and sequential procedures in research, development, engineering, manufacturing and marketing, but an enforced integration of product design to the manufacturing technology and product design of the end-user. This explains the observed forward integration of materials producers and backward integration of materials users. These observations acquire added significance when viewed in conjunction with the increasing application of microelectronics based flexible automation technologies across manufacturing and the trend towards a systematic integration of all aspects of the production process in computer integrated manufacturing. Some of these aspects will be examined further on.

New approach to costs: total system costs

New materials, which in general are more expensive than existing materials, especially metals, necessitate a different approach to costs by end users. To take advantage of the properties and performance characteristic of a new material, end-users need to redesign both product and manufacturing techniques. Hence a system-wide total approach to costing must be taken, where potential savings in tooling, assembly, fabrication, maintenance and life-cycle costs could offset the higher advanced materials cost. It is no accident that many current applications of advanced materials are in areas, such as military or aerospace, where performance is more important than cost, at present.

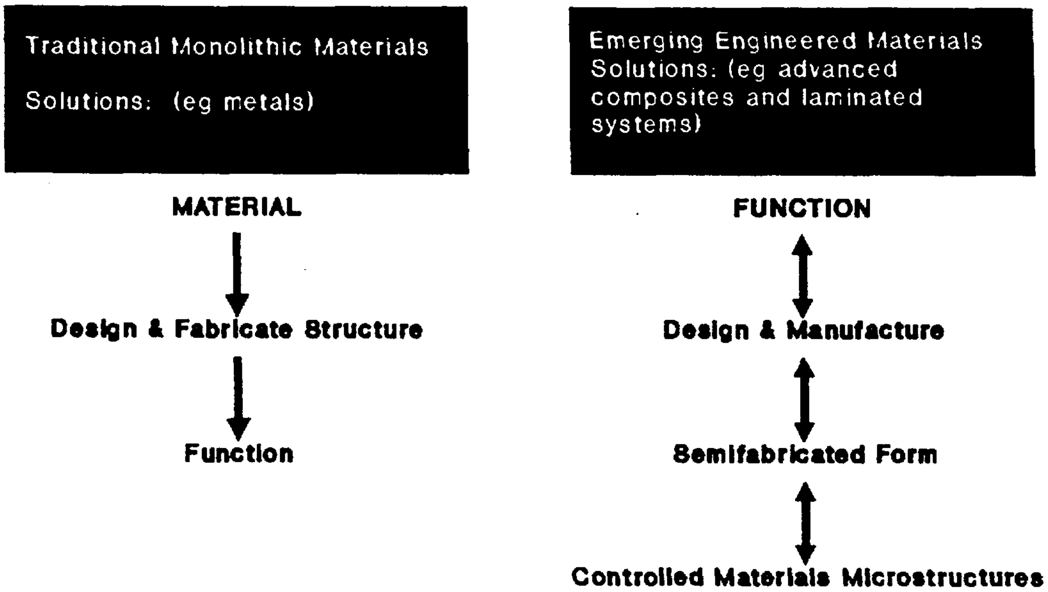


Fig. 5: Advanced materials systems: Integrating materials, manufacturing and product design

Source: Alcoa, Position Paper from the 10th Biennial Conference on National Materials Policy.

The long run importance of "materials systems"

An important view in industry is that the performance requirements for materials for current and future use require the development of combinations of materials or engineered "materials systems" for which microstructure is so designed as to maximise the properties of the constituent parts as well as that of the whole. Stringent specifications for extremely demanding performance criteria from end user product designers requires overcoming the limits on engineering flexibility and performance optimisation encountered in today's monolithic materials. Engineered materials systems can combine materials from the same on different families as shown in Figure 4. Such complex materials needs further strengthen the integration of materials science, product design, manufacture and a planned, cohesive marketing capability in close contact with materials and end-users. Further, it signals the transformation of existing monolithic materials producers into integrated, large materials producers. It is those companies that combine the necessary scientific and engineering expertise and experience, together with appropriate marketing, sales and collaborative strategies with end users that will emerge dominant in the next two decades.

Advanced materials systems with their attendant vast scientific and engineering requirements and testing, instrumentation and research expenditures are proving beyond the means of individual companies. Hence, this has already led to large collaborative efforts and consortia between industrial companies, universities and governments. This will increasingly become one of the major features of the materials revolution.

Materials science and engineering 1960s-1970s: the onset of flexibility and purposive creativity

By way of concluding and summarising the foregoing we wish to highlight some crucial aspects of the materials revolution.

Materials science and engineering as has emerged from the 1960s onwards is predicated upon an inseparable linkage between science and engineering technology, and a necessary integration of several different fields within the sciences (e.g. physics, crystallography, inorganic chemistry) and technology (e.g. metallurgists, ceramicists, electrical and chemical engineering). The aim, orientation and underlying philosophy of this organic multidisciplinary linkage is to provide scientific and technological answers to the design and production of new materials engineered for specific uses. To do this, MSE uses scientific understanding (which derives from theory, advanced instruments, experimental techniques and experience) to (a) delve into the microstructure and composition of materials, (b) connect these insights to their properties and performance and (c) use this information to process and shape the designed materials in a controlled manner so as to produce materials with the required properties and performance in use in the finished product. Thus MSE translates fundamental understanding of atomic and molecular microstructures into the performance of materials and end products.

Throughout its relatively short existence, MSE has, in fact, engendered great flexibility in the manufacturing process and business strategy, by the very process of being able to resolve materials bottlenecks and constraints in particular applications, by offering a great many options to materials users, ever improving quality inputs for new and improved product designs, especially during a period in which the industrial system is undergoing an internal transformation characterised by flexibility in production and market response. In this, MSE brings with it from its very inception the concept of purposive creativity: that is, the use of an expanding scientific and technological knowledge in a directed, purposive manner to meet specific material needs or to create entirely new theoretically predicted materials. Within the realm of its close concern with and connection to customer and market needs it, importantly, has the intrinsic ability to both respond to end-use technology or market push and to autonomously create new materials without an existing designated use, but which can lead to entirely new designs, products and industrial activities. Thus, in the very nerve centre of the functioning of industrialised economies is located a powerful agent for resolving constraints and facilitating change, very much at one with the organisational and technological circumstances and requirements of this stage in the evolution of industrial organisation of market economies. Such purposive materials creativity and consequent flexibility promises to be a dominant influence in the form, pace and direction of technical and industrial change in the 1990s and beyond.

ISSUES AND DEFINITIONS: NEW ADVANCED MATERIALS; WHY NEW? HOW ADVANCED?

In the early part of this century, the new discoveries in atomic physics and the nature of the chemical bond led to massive research at the university and industry levels into the fundamental nature of the solid state. New metallographic techniques enabled a systematic study of the microstructure of alloys, leading to new alloys which were only empirically explored earlier, as, for example in 1904, the low carbon iron-chromium alloys.

World War I, and the use of mechanised warfare, was essentially an iron and steel (and aluminium) war. Advantage in weapons technology derived from relative superiority in steel ingot forging, foundry and metal working technologies. At the same time, the emerging automotive industry was giving rise to precision manufacturing and mass production techniques. Precision manufacturing was aided by Guillaume's development of ultra-low thermal expansion nickel-steel alloys for use in precision metrology.

It was only during the inter-war years that the scientific advances in the fundamentals of the laws and structure of matter began to lead to industrial breakthroughs, for example as in Du Pont's "Purity Hall" Laboratory work between 1928-1937 into the synthesis of high molecular weight polymers. Major fields of importance at the time were solid state physics, synthetic polymers and elastomers, and modern ceramics and glasses. During the 1930s-1940s, refinements in X-ray diffraction and dislocation theories, together with further developments in solid state physics began to make serious inroads into metallurgy, with the emergence of the important sub-discipline of physical metallurgy. Until the onset of World War II, it was Europe that dominated the physical sciences and engineering.

World War II was also a materials war which, moreover, gave an unprecedented impetus to R&D on new materials. The war effort itself required advanced armour steels, improved precipitation-hardened aluminium alloys for airframe structures, and high alloy steels for tooling, penetrators, aircraft engines and turbo superchargers. At the same time, new materials and alloys systems had to be developed to substitute for, or conserve, critical metals and natural rubber. The development of atomic weapons entailed intensive studies into metallurgical properties and the development of advanced materials for atomic weapon components, while the development of speciality graphite, aluminium and brazing alloys with low nuclear cross-sections that could withstand the extreme environments in nuclear reactors was necessitated by the subsequent emergence of nuclear power. Research into electronics accelerated in order to meet military requirements for communications, transport, navigation and intelligence systems. At the conclusion of the war, the United States of America had emerged supreme in most fields of science and engineering. Materials research had acquired both prominence and support within government, universities and industry. Progress in the science of the solid state led to a proliferation of new materials, such as new polymers, high performance metals and superalloys, as well as the invention of the transistor. In the USA, research on new materials became a major part of the work of the

National Science Foundation (established in 1950) and progress was made along several fronts in many Federal laboratories and the National Aeronautics and Space Administration (NASA).

The launching of Sputnik I by the Union of Soviet Socialist Republics (USSR) in 1957 subsequently led to the establishment of several interdisciplinary laboratories (IDL) after 1960 for materials research in the USA. In fact, the development of space programmes, and ever more sophisticated weapons and defence systems in the 1960s and 1970s, were predicated upon improvements in solid state electronic devices and components, as well as new materials for high performance extreme environment applications.

Hence, the period since World War II has seen an enormous proliferation of new materials and processes. What is more, the development of nuclear power, electronics, aerospace and weapons systems, necessitated the development of advanced materials engineered to meet the exacting specifications and stringent performance requirements in each application. At the time of their development such materials could be viewed as advanced materials, which subsequently became more widely commercialised.[3]

New advanced materials

There is a sense in which all materials are now ''new'' materials. The revolution in materials science and engineering (MSE) cuts across all classes of materials leading to vastly improved processing and properties of all existing monoliths, the use of surface modification technologies, such as ion implantation, thermal spraying and chemical vapour deposition to greatly improve the properties and performance in use of traditional materials, and the emergence of laminates and composites as a preeminent class of materials systems in synergistic combinations. New advanced materials refer to the accelerated development and (eventual) commercial or military application of higher performance, knowledge-intensive, high cost, low-volume, customised materials in the last 10-15 years, which are the outcome of recent advances in processing technologies and in materials design, synthesis and characterisation capabilities based on an in-depth understanding of the micro structure-processing properties of matter continuum. We therefore place considerable importance on the scientific and technological developments in the 1980s and their impact on the materials sector. Indeed, the events of the 1980s mark a discontinuity with past experience in the mode of design, processing and utilisation of materials in industry, with the massive infusion of science and advanced, computer-aided instrumentation at all stages of materials design, development and application. We do not yet have clearly defined guidelines as to what constitutes an advanced material, and this varies across materials classes and applications, but we can delineate in specific cases. Commodity primary aluminium ingot is not, but the recently developed aluminium-lithium alloys for aircraft use, are advanced materials. At the same time, we note that the new scientific and engineering base facilitates the attainment of higher quality and performance characteristics in traditional materials as well, through the use for example, of advanced processing technologies and quality control.

The United States Bureau of Mines[4] takes as its starting point the development of new materials since the 1960s. New materials are defined as those commercialised in the last three decades. When first commercialised they may have been considered as advanced materials. Subsequently, some of these grew in volume and became more standardised high-performance materials, descending to the status of engineering materials. Still others passed even this stage and became high-volume conventional or commodity materials in wide use, constituting over 90 per cent of the value of the once new materials. The value of what they define as advanced and engineering materials (A&E) is perhaps only US$ 5 or US$ 6 billion in the USA. If we look at commodity polymers commercialised on a large scale in the last three decades, their value totalled US$ 22 billion, while the value of around a dozen A&E polymers in the USA was less than US$ 2 billion. It is of course very difficult to quantify the importance or value of A&E, given the lack of agreed definitions, industrial classifications and available data as currently collected. A&E materials are high cost, low volume materials tailored for specific or few applications. Some are designed for only one or few applications, whereas others, such as specialty electronic ceramics, can have wider applications across several electronic devices. A&E materials are knowledge and technology intensive materials, emerging out of technology – and often labour- and skill- intensive production processes. Many are tailored to meet the most exacting specifications and demanding performance requirements, which cannot be met by traditional materials. Some advanced materials are not mere improvements upon existing materials, but rather make possible an entirely new product or industrial process of which they form a part. They are therefore enabling technologies.

The USA constitutes the largest market for such materials, and the growth of consumption between 1985-2000 is forecast to be around 7.5 per cent per year for A&E polymers and 6 per cent per year for A&E metals and alloys. Many of the advanced materials which are expected to grow from current smaller bases to future commercial application are expected to grow faster, as for example, 10 per cent per year for aluminium lithium alloys, 14 per cent per year for advanced ceramics, and up to 25-35 per cent per year for intermetallic alloys, metal matrix composites and advanced polymers. It is important to note that the projections for advanced materials markets by the year 2000 were revised downwards in mid-1993. This applies also to the 1990 UBSM tables presented below.

If we take this view of the development of new materials, then if we look at metals, for example, there have been great improvements in most of the age-old alloys known through progress in metallurgy, production methods, analytical tools and process controls. But the recent emergence of major new processing technologies enable not merely a better microstructure for metals produced by conventional methods, but have also ushered in an array of new metals and alloys which are only possible by these latest technologies. For example, rapid solidification techniques produced amorphous alloys and mechanical alloying has resulted in metastable alloys and powder metallurgy in oxide dispersion-strengthened metals. Superalloys were first developed in the 1940s, and by the late 1960s most of the principal high-temperature superalloys had been formulated with their servicing temperatures levelling around 950°-1,050°C. New processing methods facilitated the subsequent development of what may be called advanced superalloys in recent years. Such methods as powder metallurgy, oxide-dispersion strengthening, directional solidification, single crystal growth, rapid solidification, hot isostatic pressing and superplastic forming have successfully produced advanced superalloy engine parts, which are, importantly, the result of precisely controlled internal structures and are thereby tailored to specific requirements in end use. Similarly, titanium alloys, first developed in the 1950s, are mainly in the A&E class of materials, but the ones that are advanced are those that have been produced by the latest processing techniques, and characterised by precisely controlled microstructures so designed as to produce specific combinations of mechanical properties. It is these very recent aspects of new advanced materials design, synthesis, processing and tailorability that we wish to stress in this paper, which herald the arrival of awesome new powers and capabilities in the scientific and engineering base of all generic materials classes, distinguishing the current period from the previous era of materials development.

The developments in MSE enable us to distinguish, for analytical convenience, between three broad groups of materials today. Greatly improved traditional, known and existing materials, through for example, the application of precisely controlled intelligent processing methods to commodity steel or aluminium production. Secondly, new advanced knowledge intensive materials tailored for specific applications, as for example, advanced steels or advanced aluminium alloys. And thirdly, entirely new materials, such as superconductors. Clearly, variations and subdivisions of these are possible. Whether known or existing materials or entirely new combinations of either or both, or entirely new materials, are involved, common to all are the micro-structure processing properties control and tailorability aspects. All are "new" materials.

In Japan the term new materials is used, which is broadly synonymous with the term advanced materials, as in the West. It is somewhat narrower than the view expressed above.

The Japanese definition of advanced materials

In 1989, MITI's Basic New Materials Study Group defined it as:

> "high value-added materials which have produced totally new epochal characteristics and new social values by driving sophisticated manufacturing processes and technologies (e.g. atomic and molecular level micro structural control, high purification and composition) and/or commercialisation technology based on metallic, inorganic and organic materials and their combinations."

Shinsozai (advanced materials) comprises two main categories. The first is materials which have been known and used for many years, but for which new uses have recently been developed. The second category comprises materials which have been newly developed. An example of the first category is stabilised zirconia. It was used in the 19th century by Nernst as a material for electric bulbs. Nowadays, stabilised zirconia is used as a new material in fuel cells and sensors. An example of newly developed material is a carbon fibre

The Japanese classification of traditional and new materials and their categorisation by function are given in Figure 6. A brief non-technical overview of the main materials developments with particular emphasis on micro structure processing properties relationships is provided.

Advanced, or fine ceramics

Traditional ceramics such as glass, pottery, tiles, bricks, plumbing fixtures and dinnerware are familiar objects in everyday applications. Advanced ceramics, on the other hand, are a result of recent technological breakthroughs which have provided a new class of materials that display distinct advantages over metals or some plastics in a number of demanding applications because of their density, resistance to stress, corrosive and erosive properties, and high-temperature operational ability.

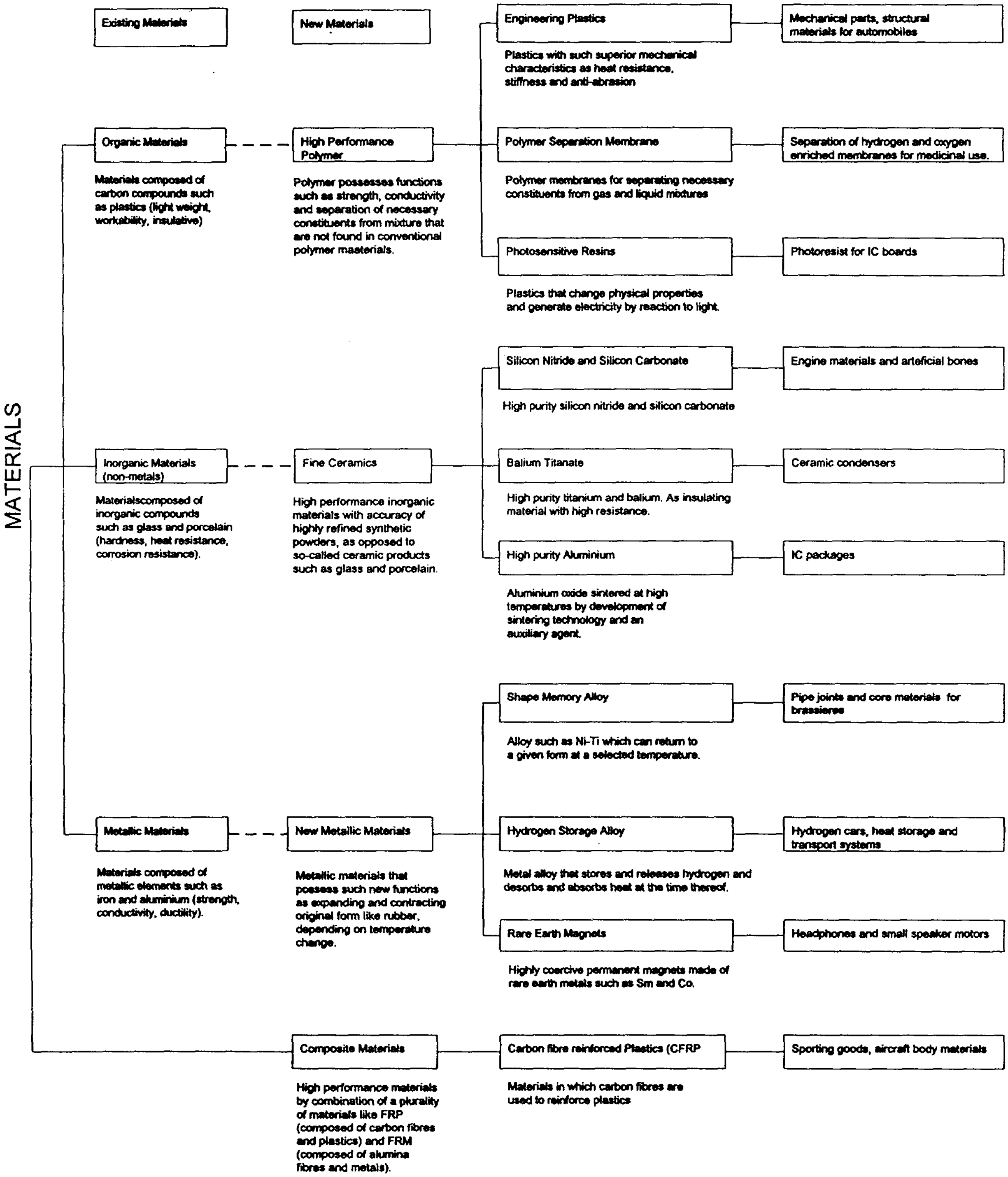
Advanced ceramics comprise a large number of materials deriving from the oxides, nitrites and carbides of silicon, aluminium, titanium and zirconium, which are processed or consolidated at high temperatures. These inorganic and non-metallic advanced materials have been developed in the last 10-12 years in response to needs arising from specific industrial and high-technology applications.

Traditional ceramic products utilise naturally occurring minerals which are mined, perhaps beneficiated, and then undergo well-known ceramic processing, such as grinding, mixing, forming and sintering. The new ceramic materials on the other hand use very high purity synthetic raw materials and powders (e.g. ZrO_2, SiC, Al_2O_3, etc.), which are processed by a range of new processing technologies that impart far superior properties to those attained in traditional ceramics.

New advanced ceramic processing technologies[5]

Hot Isostatic Pressing (HIP): The HIP of advanced ceramic materials can result in shapes and impart properties that are far superior to those obtained by other means. In the HIP process, powder or moulded articles are first encapsulated in a gas-tight capsule or in a porous coating that becomes gas-tight upon heating. The pressurised gas chamber containing the articles is placed in a hot furnace. The process allows the consolidation of dense parts via the isostatic pressure, which in turn permits sintering of more complex shapes.

Chemical Vapour Deposition (CVD): The process is one of the most successful in producing advanced ceramics with a superior combination of properties. It has been used mainly in surface modification with ceramic coatings, ceramic composites with CVD filtration and electronic ceramics. In CVD, a solid material is deposited from gaseous precursors onto a substrate, which is typically heated to promote the deposition reaction.



Plastics with such superior mechanical characteristics as heat resistance, stiffness and anti-abrasion

Materials composed of carbon compounds such as plastics (light weight, workability, insulative)

Polymer possesses functions such as strength, conductivity and separation of necessary constituents from mixture that are not found in conventional polymer masterials.

Polymer membranes for separating necessary constituents from gas and liquid mixtures

Plastics that change physical properties and generate electricity by reaction to light.

High purity silicon nitride and silicon carbonate

Materialscomposed of inorganic compounds such as glass and porcelain (hardness, heat resistance, corrosion resistance).

High performance inorganic materials with accuracy of highly refined synthetic powders, as opposed to so-called ceramic products such as glass and porcelain.

High purity titanium and balium. As insulating material with high resistance.

Aluminium oxide sintered at high temperatures by development of sintering technology and an auxiliary agent.

Alloy such as Ni-Ti which can return to a given form at a selected temperature.

Materials composed of metallic elements such as iron and aluminium (strength, conductivity, ductility).

Metallic materials that possess such new functions as expanding and contracting original form like rubber, depending on temperature change.

Metal alloy that stores and releases hydrogen and desorbs and absorbs heat at the time thereof.

Highly coercive permanent magnets made of rare earth metals such as Sm and Co.

High performance materials by combination of a plurality of materials like FRP (composed of carbon fibres and plastics) and FRM (composed of alumina fibres and metals).

Materials in which carbon fibres are used to reinforce plastics

Fig. 6: Existing and new materials

Source: K. Takeda, Basic Industries Bureau, MITI.

The SHS Method:The self-propagating high temperature synthesis method uses a combustion wave propagation itself through a reactant mixture of say, A and B, and transforming them into product AB. Combustion synthesis as a method for the preparation of materials contains the advantages of high purity of products, lower energy requirements and simplicity of processing methods.

Sol-Gel Processing: "Sol" describes the dispersion of colloids in liquids. Colloids are solid particles with diameters in the range of 10-1000A. When the viscosity of a sol increases it becomes rigid material, termed as gel. The sol-gel method consists of preparing a homogenous solution, changing the solution to a sol, gelling the sol and converting it to glass by heating. Advantages are high purity; high homogeneity in multi-component glasses; low-temperature preparation; possibility of producing glasses of new composition; simple facilities (but expensive stacking materials).

Organometallics: Organometallic chemistry has recently been used to produce complex ceramic shapes for use at ever higher operating temperatures. Such processes include polymer pyrolysis to form graphite fibres, SiC fibres and mixed $SiC-Si_3N_4$ fibres, hydrolysis of metal alkoxides to form sol-gel glasses and CVD of organometallic compounds, such as methyltrichlorosilane to produce silicon carbide films. Organometallic routes offer advantages such as higher purity, more complex shapes of fine ceramics and novel ceramic alloys.

Plasma Processing: Thermal plasma processing involves melting and remelting technologies, plasma metallurgy, including extractive metallurgy, plasma deposition and rapid solidification techniques, plasma-synthesis and consolidation and other industrial applications that make direct or indirect use of thermal plasmas. Apart from a few notable exceptions thermal-plasma processing is at the laboratory or pilot stage, but there is a consensus of opinion that these emerging technologies will have a strong impact on the economy.

Injection Moulding: Injection moulding is a low cost, high volume process for making net-shaped, or near net-shaped parts used extensively in the plastics industry to produce complex shapes. Ceramic parts are made with similar moulding equipment, but the dies are of harder, wear-resistant metal alloys. It is currently developed for net-shaped forming of complex aerodynamic rotating and stationary components for prototype gas-turbine engines by the Ford Motor Company and the Garrett Turbine Engine Company in the USA.

APPLICATIONS: Advanced ceramics have widespread applications, hence their importance. Seven broad groups can be identified:

> **Electronics:** Advanced ceramics are used in integrated circuit (IC) packages, capacitors and resistors, and therefore have enormous potential in the high growth market of electronic components. Another highly important application will be in integrated optics (i.e. optical guided-wave devices that perform processing functions on the light beams they guide), which

will play a revolutionary role in fibre-optics communications systems, probably the major telecommunications technology of the future. They will also increasingly be used in sensors installed in robotics, cars, automation, medical implants (bioceramics) and many other industrial and consumer applications.

Engines: An important structural application of advanced ceramics in the form of silicon nitride, silicon carbide and zirconia is in gas turbines, diesel and gasoline engines. Several hundred millions of dollars have hitherto been spent on demonstrating technical feasibility in terms of new materials and engineering technology. Nevertheless, there remain significant problems in terms of cost, reliability and manufacturing capacity. In order to achieve advanced designs in aerospace, propulsion capabilties must be dramatically improved. Ceramics can withstand operating temperatures of over 1,600°C, which is far beyond the maximum temperature capabilities of superalloys, thus increasing combustion temperature and improving thrust to weight ratios. Therefore large efforts are underway to develop ceramic parts for next generation, high performance military aircraft, which would account for about 30 per cent of turbine engines by the year 2000. Technical experts give the following time frames for applications, but it is more likely that automotive and aircraft turbine engines will appear after 15 years due to major technical and economic problems (Table 1).

Cutting tools and machine parts: Existing cutting tools are reaching their limits and they need to use tougher new alloyed metals. Tools made from advanced ceramics are showing distinct advantages over metallic counterparts, especially in competition with tungsten carbide-cobalt cermets, facilitating higher speed, reduction of costs (60-75 per cent) and enhanced productivity gains. Nowadays, they are almost a necessity in NC machine tools. They also exhibit large potential in parts such as heat exchangers for industrial furnaces, seals, valves, nozzles, wear pads and grinding wheels.

Table 1: Time frame for applications

Period	Advanced Ceramics in Engine Development
1984 – 1987	Ceramic parts
1987 – 1990	Ceramic components
1990 – 1995	Systems
1995 – 2000	Small gas turbine engines

Industrials products: The resistance to corrosion and erosion of advanced ceramics has won them new applications in the metals industries, chemical processing, oil and gas industries and precision jigs in the manufacture of electronic components.

Consumer products: Commercial application currently in use, especially in Japan, include sporting equipment, scissors, knives, etc.

Energy: Here, application includes batteries, fuel cells and solar collectors.

Space, aerospace and defence: Heatshields and tiles for space missions and re-entry vehicles, infrared windows, radomes, armour, military engines, high-performance aerospace bearings, etc. They are also evaluated for use in high-temperature aerodynamic surfaces where operating temperatures exceed those sustained by current metallic alloys.

IMPORTANCE: Advanced ceramics possess properties that make them superior in many demanding high-temperature, high stress, corrosive applications which subject materials to intense wear and heat. They can be lighter than metals, thus offering energy saving potential. Their use may also offer cost advantages to the user industry via process and product redesign. Advanced ceramics (and composites) could be viewed as structures rather than materials. Overall systems costs, taking into account integrated design, fabrication, installation and life cycle costs, would render advanced ceramics competitive with conventional materials and metals in many applications. (See Tables 2 and 3.)

Advanced ceramics are viewed as a key competitive technology in the current and future global market. Early studies[6] by the Congressional Office of Technology Assessment and the United States Argonne National Laboratory, identified advanced structural ceramics as of major importance to the national economy, predicting that failure to remain competitive in this field would cost the economy tens of billions of US dollars in terms of Gross Domestic Product (GDP) and hundreds of thousands of jobs by the turn of the century. Of the current US $30 billion world market for advanced ceramic materials, Japan controls 50 per cent and is dominant in the market for ceramic electronic components. The importance of such materials springs not merely from the sector *per se*, but also in terms of the diffusion of new materials and technologies throughout the rest of the economy. This would confer cost and performance competitive advantages in a broad spectrum of industries, benefiting exports, output and employment. For example, it is estimated[7] that domestic production of automotive engine components could add as much as US$ 279 billion to the USA's GDP over 20 years and generate 250,000 new jobs.

The use of advanced ceramics in industrial processes could result in dramatic gains in fuel efficiency, permitting the raising of their maximum operating temperature from 1,800°F to 2,700°F. There are tremendous gains then to be made in terms of engineering efficiency, higher productivity and lower costs in a multitude of industrial applications. What is more, advanced ceramics are seen as a means of reducing import dependence of Western econo-

Table 2: Characteristics of advanced ceramics

Advantages	
High melting point	Good dialiectric properties
High stiffness	Thermal/electric insulators
High hot strength	Semiconductor properties
High compressive strength	Ion-conductor properties
High hardness	Magnetic properties
Wear and corrosion resistance	Biocompatibility
Low density (light weight)	Abundant raw materials
Limitations	
Susceptible to thermal and mechanical shock (brittle)	
Gaps in understanding and experience	
Difficult to fabricate	
Poor reproducibility	
High cost	

Source: E.J. Kuber: **Structural Ceramics: Materials of the future in advanced materials and processes, 8,** 1988.

Table 3: Benefits of structural ceramics in selected applications

Application	Benefit	Materials
Light-duty diesel (uncooled)	10-15 per cent reduction in fuel consumption	Zirconias Silicon nitrides silicon carbides Aluminas Al-titanates
Heavy-duty diesel (adiabatic	22 per cent reduction in fuel consumption	Zirconias Silicon nitrides Silicon carbides Aluminas Al-titanates
Recuperator for slot forging furnace	42 per cent reduction in fuel consumption	Silicon carbides
Machining of gray cast iron	220 per cent increase in productivity	Silicon nitrides
Extrusion dies for brass	220+ per cent increase in productivity	Zirconias

Source: R.N. Katz: "Advanced Ceramics Overview & Outlook", US Bureau of Mines, Advanced Materials;

Table 4: USA advanced structural ceramics market, 1987*
(Millions of current dollars)

Application	Value of Ceramic Content
Aerospace and defence related	20
Automotive	29
Bioceramic	8
Cutting tools	32
Heat Exchangers	7
Wear parts and other industrial	57
Total	**171**

* Includes ceramic composites

Source: Abraham: in US Bureau of Mines, **The Materials Society**, 1990.

mies for a number of strategic minerals such as chromium, cobalt, tungsten and manganese. In fact, this has been a major reason for the research thrust in this area since the 1970s. But, although the resource base for advanced ceramics is plentiful the fear is that import vulnerability would simply be transferred to advanced ceramic powders and components in critical and high-tech or military applications.

Table 5: Forecast USA advanced ceramics markets
(Millions of US dollars)

Application	1990	1995	2000
Electronics	3,740	6,565	11,360
Structural:*			
Aerospace and defence related	80	200	445
Automotive	81	310	820
Bioceramics	15	34	60
Cutting tools	92	246	500
Heat exchangers	15	50	100
Wear parts and other industrial	150	320	720
Total	433	1,160	2,645
Grand Total	**4,173**	**7,725**	**14,005**

*Includes ceramic composites

These materials have the potential therefore to change global patterns of materials production, sourcing, trade flows, global and domestic location of industry, and industrial structures. For example, domestic location is already changing due to the lighter weight of components away from traditional lines of products shipment. Global location would be determined by the need to cater for domestic niche markets, flexible and fast response to the needs of manufacturers employing JIT methods of flexible production, tariffs, and the emerging triad of global markets.

Future market sales for advanced ceramics appear very favourable. The current commercial position indicates that electronic ceramics dominate overall market segments, with over 80-90 per cent of the whole market. Figures for the USA market are given in Tables 4 and 5. The applications of ceramics to microelectronics is given in Table 6.

Electronic ceramics are forecast to grow over 10 per cent per year until the year 2000, supplying the massive global electronics industry (US$ 426 billion in 1987), which is the largest user of its products. By that time structural ceramics will come into increasing use, reducing the market importance of electronic ceramics to 60 per cent. Japan consumes about 74 per cent of total volume and 66 per cent of total value of electronic ceramics, with a strong position in global markets. Nevertheless, USA and Western European suppliers maintain a technological edge in systems design, and are orientating their efforts in markets not dominated by Japan with non-consumer areas registering high growth as in computers, cars, and telecommunication industries, and the military sector (where foreign sources are disallowed).

The packaging materials[8] used for electronic integrated circuits (IC) used as mounting platforms for even the most sophisticated IC chips, can be either ceramic or plastic. Traditional materials have been dominated by forms of aluminium oxide, and less so by beryllium oxide. Over the last 10 years, IC chip complexity has increased by 16 times, as the chips are becoming smaller, faster and generate much more heat. Thus a new family of materials are required to meet the requirements of space efficiency, surface mounting, reliability, ease of assembly of chips, better signal propagation and lower cost. New materials include glass ceramics and aluminium nitride.

Currently Japan supplies more than 90 per cent of all IC packaging materials, and the USA consumers over 50 per cent of the global production (with military applications taking 45 per cent of this).

In Japan[9], advanced ceramics was recognised (very early in the 1980s) as a major new technology for restructuring Japanese industry into the 1990s. There was a surge of new entrants in fine ceramics in Japan in the early 1980s when it was recognised that it was a material of fundamental importance to industry and defence. This occurred despite the lack of defence and aerospace research in Japan, and the fact that advanced ceramics research originated in the USA defence programmes. Many Japanese firms have switched their production and research efforts into fine ceramics to take advantage of the opportunities offered by the new materials to replace metals and plastics. Interestingly, the firms diversifying into this area came from the severely depressed traditional ceramics industry (since the 1970s), traditional glass, cement and chemicals companies and electronics firms. While the United States is the world leader in advanced ceramics R&D, especially in high performance ceramic matrix composites (CMCs) aimed for the aerospace industry, it continues to rely on European and Japanese firms for the supply of high-grade ceramic powders and reinforcements. Japan leads in non-aerospace monolithic ceramic applications, dominating the market for electronic ceramic packages. Moreover, large Japanese ceramic companies are collaborating with car producers for the resolution of technical constraints in the use of ceramic components in engines. Although Japan posseses limited capabilities in CMCs, it does have considerable expertise in ceramics processing.

Table 6: Applications of ceramics in microelectronics

Information Processing Technology	Application	Ceramic Materials
Information processing	Substrate	Al_2O_3, BeO, SiC, AlN
Package	Dielectric	Si_3N_4, Sio_2
Device	Mask	Borosilicate glasses
Information storage	Disk	Iron oxide, ferrite
	Tape	Chrome oxide, ferrites, glass
	Head	Al_2O_3 + TiC substrate
Information display	Dielectric	Lead-borosilicate glass
	Seal	Lead-zinc-borosilicate glass
	Face plate	Soda-lime glass
Information printing	Ink jet	ZrO^2-containing glass
	Electroerosion	Ceramic-metal composites
Information transfer	Optical fibre	SiO_2, B_2O_3-SiO_2

Source: Roa R. Tumala: **American Ceramic Society Bulletin** 67, 1988.

Commercialisation barriers

Research in this area is aimed at enhancing the scientific pool of knowledge, improving characterisation of this class of materials and developing processing technologies for reliable, reproducible, low cost competitive ceramic products. In fact, the major problems arresting the widespread use and diffusion of these materials are the poor manufacturing techniques and brittleness.

Ceramic materials are very susceptible to small flaws, such as cracks, voids and inclusions. This increases the importance of controlling processing and finishing as closely as possible. Flaws can occur at any stage of the multistage fabrication process from powder production, powder conditioning, shaping and designification, and cannot be corrected at later stages. In fact, flaws will always exist in ceramic parts, the design of which therefore becomes a statistical process as compared to metals in which it is a deterministic process. It is important therefore to identify those conditions in the early processing stages that create defective products and to detect critical flaws in the fine powder itself. *In-situ* non-destructive techniques become important to monitor the process, characterisation and end product inspection to remove defective parts. Another method to reduce the probability of failure is to design the microstructure of the materials so as to increase resistance to fracture (increase toughness). This can be achieved through a refinement of the polycrystalline grain size and shape, transformation toughening and composite reinforcement. In the last 15 years there have been tremendous developments in the field of toughening ceramics. In the last decade, there have been dramatic improvements in the mechanical properties of structural ceramics. This has been possible because of the availability of highly sinterable powders plus hot isostatic pressing and the incorporation of new toughening mechanisms, such as transformation toughening and fibre and whisker reinforcement, by "crack-tup shielding"[10]. In ceramic matrix composites, the ceramic matrix is reinforced with high strength fibres, whiskers and fibres. In most high performance applications, as in aerospace, continous fibre CMCs that exhibit superior toughness are favoured. More work is required in the areas of improving the reliability of the matrix/reinforcement interface and low-cost processing techniques. Another solution lies in the greater use of ceramic coatings, which confer high-performance advantages and wear resistance on super-alloy components, thus avoiding the brittleness of monolithic ceramics.

The other major problem with advanced ceramics lies in the difficulties encountered in their additive manufacturing processes. The material is formed to its final shape simultaneously with the forming of the internal microstructure. A central need in designing such materials is to consolidate as many components as possible into a single structure. This is due to the fact that finishing and fabricating are excruciatingly difficult due to the hardness of the material, and are also very expensive. Hence, the aim of design and fabricating is always near-net-shape processing so as to produce a final product that requires very little machining. In metals, near-net-shaping processes used include powder metallurgy and advanced casting techniques. In general, advanced ceramics are in direct competition with metals and are more expensive than the latter. This necessitates that near-net-shaping of ceramics must be a top priority if they are to be cost-competitive with metals in the future. Major components of production costs include finishing and machining techniques. All in all, a crucial barrier to wide commercialisation of advanced materials remains the development of low cost, reliable and reproducible fabricating of components to final net-shape.

Progress requires[11] further research on processing, microstructure and desired final properties interaction, the design of brittle materials (which is severely lacking at the moment), process control, non-destructive evaluation, understanding crack growth process and life prediction. Another important point is that the fabrication process remains very labour and skill intensive. Research efforts are aimed at reducing both the labour and craft-skill content of the production process.

Advanced polymers

Polymers[12], or plastics as they are commonly known, are organically derived and synthesised materials that can be moulded at high temperatures and will then retain their shape when cooled. Commodity plastics, such as polyethelene, polystyrene and polyvinyl chlorine, have been the backbone of a large and growing plastics industry since the 1930s. Commodity plastics are high volume, low cost per unit materials in contradistinction to what are known as engineering polymers (or plastics), which are of recent origin and have low-volume output and high unit value.

Engineering, or high-performance plastics, possess exceptional strength and/or heat resistance in comparison to commodity plastics, and are increasingly used in automobiles, aircraft and many other applications. They include polyphenylene oxide, polyethelene terephthalate, polyacetal and alloys and blends of these polymers. Performance polymers with decomposition temperatures as high as 530°C include fluoropolymers, polyarylate, polyethereketone and others. Such materials can be reinforced with a variety of fibres to form polymer matrix composites with applications to both exterior and interior components of aircraft, automobiles and other structural applications with high expected growth rates. Research is underway[13] for the use of polymer materials in optical fibres, semiconductors, electrical conductors and so on, placing them in direct competition with metallic and ceramic materials.

Another important subdivision of plastics is in terms of thermoplastics, which can be repeatedly resoftened and rehardened, and thermosets, which cannot be resoftened after hardening by raising the temperature. Resins are organic liquids or solids that are plastic materials which can be used to build more complex plastic compounds.

Currently the most widely used material in the USA, outpacing on a volume basis the consumption of steel, copper and aluminium combined, is plastics. During World War II plastics were in increasing demand as substitutes for natural rubber. In the 1950s large scale production reduced unit costs and led to penetration of the markets for metal, wood and glass. Following saturation problems in the 1970s, there has been some resurgence of the industry in recent years due to the technological advances in the field of polymer blending to obtain properties greatly superior to those of the constituent elements. The growth rate of plastics in the USA market is estimated at 3-5 per cent until 1990 and 4 per cent thereafter until 1995. But high performance polymers in the form of reinforced plastics and composites is forecast to grow at 25 per cent per year in the 1990s. The USA and world consumption of advanced polymers is given in Tables 7 and 8.

Table 7: Consumption of A&E polymers

	USA (1,000 metric tons	World (1,000 metric tons	USA (million US$	World (million US$)
1985	510	1,410	2,200	6,000
1990	760	2,020*	3,600	9,600
1995	1,050	2,690*	5,800	14,850

*Arthur D. Little Resources (7).
Source: United States Bureau of Mines: **The Materials Society**, 1990.

Clearly the major plastics producers are large oil companies, since the principal raw materials for plastics are petrochemicals (ethylene, propylene, and benzene) derived from petroleum. About 85 per cent of the basic industrial chemicals are used in industrial polymer production, with most of the organic intermediaries deriving from oil and natural gas. This is a point that needs to be stressed, since in discussing materials issues the large shift from inorganic to organic mineral inputs (and their geographic distribution) are often ignored. This implies dependence of IACs (industrially advanced countries) plastic industries on oil and feedstock from abroad.

Table 8: USA Consumption of A&E Polymers by Industry (thousand metric tons)

	1985	**1990**	**1995**
Aerospace and automotive	115	170	260
Electrical and electronic	140	185	285
Building and construction	65	100	95
Home appliances	35	65	75
Other	155	240	335
TOTAL	510	760	1,050

Source: US Bureau of Mines: *The Materials Society*, 1990.

Hydrocarbon feedstocks for chemical products

The modern plastics and synthetic fibre and rubber products are mainly obtained from petrochemical feedstocks. Chemical production normally locates in the proximity of oil refineries. Trends in the industry's production of industrial organic minerals favour the location of chemical plants near natural gas or oilfields. Figure 7 below, shows the major petroleum and gas based basic petrochemicals, intermediates and polymers derived from them.

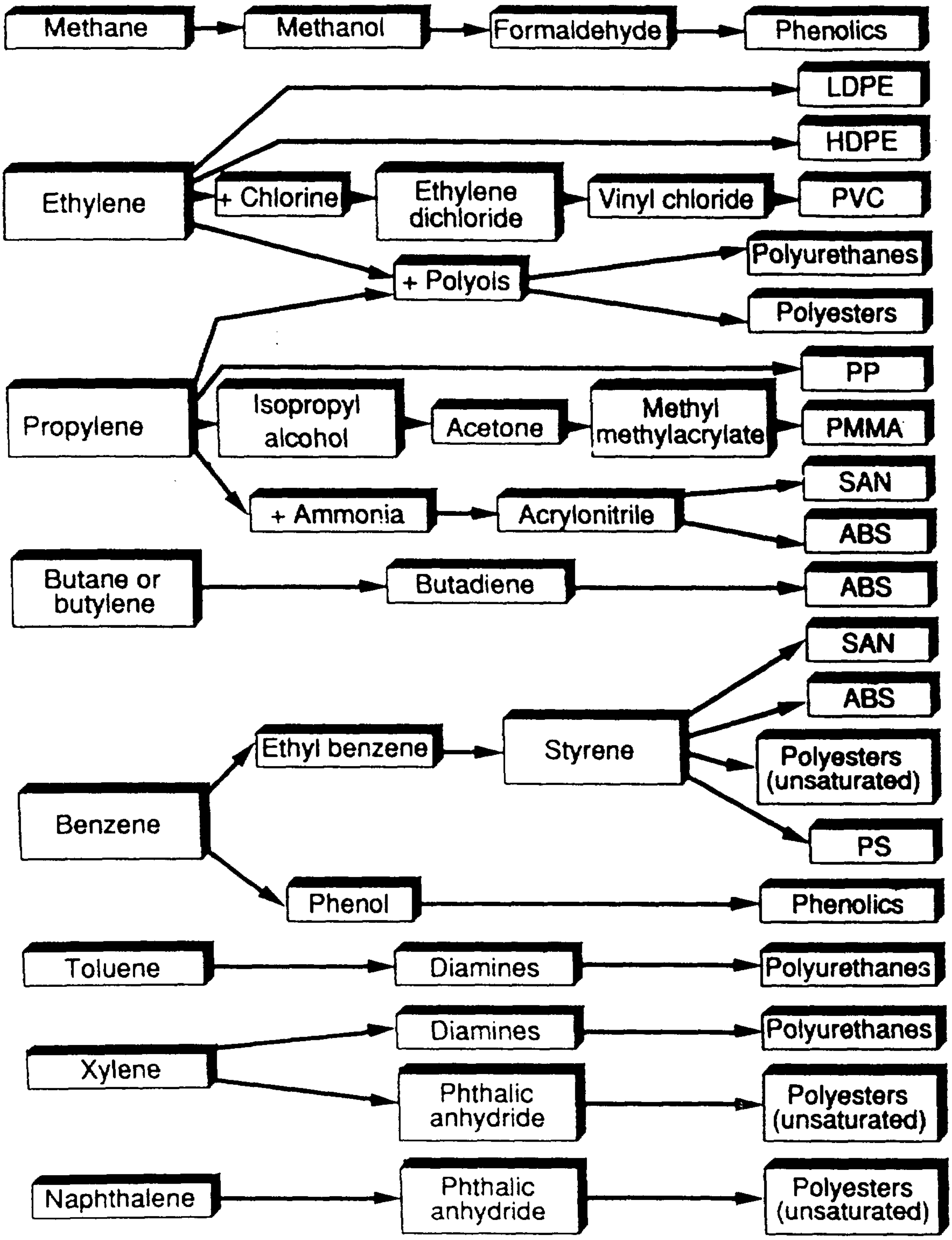
From monomers to engineered polymers

Polymers are at the root of many natural products, such as wood cellulose, starch, resins and proteins. A better understanding of their molecular makeup has led to the development of synthetics. Polymer based plastics are a large market, but conventional plastics are reaching saturation point in their conventional applications.

Advanced polymers or engineered polymers are being developed to such sophistication that they are pushing into markets dominated by metals. The major use of the new polymers is in composition, both as fibre and matrix. The majority of composite materials makes use of polymers, but composite products are only a small fraction of the class of products known as engineering polymers. Again, the materials revolution has meant greatly increased knowledge of the microstructure – properties relationship in polymers, with advances in synthesis and new processing methods based on such intimate knowledge, leading to materials of unprecedented properties.

Polymer science can now tailor make polymer molecules. The latter are made from smaller units called monomers. The way monomers are chosen and assembled determines the properties of the bulk material which comprise them. The polymer so structured or engineered can then be tailored via processing on a larger scale, like a metal or a composite, and given a desired microstructure.

The shape of the polymer molecule and its chemical make-up have an influence on the properties of the bulk material. And by varying the characteristics of polymer chains we can create a desired microstructure. Polymer scientists and engineers however, go beyond this simple building up of a microstructure. They start with a "synthesised" molecule and then, through processing, they transform its structure and properties. One type of processing is blending. For example, to increase toughness a brittle amorphous plastic can be blended with another to combine the best properties of several materials. There have been recent advances in processing which extrude several polymers, and scientists are now trying to synthesise and process polymers so as to increase their performance under stress, heat, chemical attack and even exploit their electrical properties to serve in electronic systems. Today, the major research thrust is in the direction of improving the performance of known polymers, rather than the invention of entirely new polymers. With greater scientific understanding of the principles underlying the successful production of improved polymers and of the attainment of previously unachievable combinations of properties by combining



Source: US Bureau of Mines, **The New Materials Society**, 1990.

Fig. 7: Materials flow from feedstock to resin

two or more polymers, an increasing number of commercially available modified and blended polymers has appeared in the market. Blends are likely to continue to proliferate in the future due to the fact that tailoring of multicomponent polymer systems is less expensive than producing an entirely new homopolymer. Given this ability to synthesise molecules and use processing techniques to improve mechanical properties for structural application of advanced polymers, scientists are looking to hierarchical organisation embodied in biological tissues. In fact polymer matrix composites imitate such structures. Biology has pointed the way to designing polymers as systems for particular use: polymers in the 21st century will not be used as monolithic materials, but as materials systems in complex, delicately structured combination of materials. Composite materials are discussed below.

Advanced metals

In the past, metallurgical practices were informed by empirical methods and accumulated experience in deciding as to the appropriate alloying elements and processing path required to produce an alloy. This position has now radically changed. Materials scientists can now intervene at the atomic level and, given a deep understanding of metallic cyrstalline lattices and the role of defects and dislocations in determining properties, design specific alloys for high performance applications[14]. That is, advanced metal alloys are generated by manipulating defects in the cyrstalline structure so as to produce desirable properties in terms of ductility, low brittleness and performance at high temperatures, vibration and corrosive environments, as in aircraft engine applications. In fact, most research and development of advanced metals has been guided by the increasingly stringent requirements for high-temperature performance as producers are striving for higher energy efficiency in aerospace. The performance requirements of advanced aerospace systems continue to increase. Hence the mechanical properties of the material inputs must also continually improve. These properties are a result, not only of defect free materials, but also of the presence of irregularities, such as voids, gas-filled pores, second-phase particles and the segregation of alloy constituents. Ability to institute careful processing control of such defects results in a better performing material with assured quality, therefore facilitating the system performance[15]. New alloy developments and new advanced processing techniques for cost-competitive metal production have also responded to demands for higher performance materials coming from most other industries, such as oil companies drilling deeper, hostile environments, and the chemical processing industry's search for improved process efficiencies and corrosion resistance. We should also point out that advanced metal product and process innovation, spurred on by steel and aluminium, are competitive technological responses of metals industries to saturation of traditional markets, recession, cost and price squeeze pressures in commodity metals, and competition in traditional markets from advanced engineered materials such as composites and plastics. It is therefore an attempt to remain competitive and cost efficient in existing markets, as well as expand markets and acquire a competitive edge in new applications. The current emphasis in the steel industry for example, is on processing techniques that can lead to cost reduction and product improvement. Steel makers are hoping that car firms will take up their flat rolled products in preference to plastics and light metals, both in body panels and cast and forged autoparts. On the other hand, aluminium executives forecast a rising use of aluminium in cars in 1992 and beyond due to stricter corporate average fuel economy requirements, changing fuel prices and concern over emissions. There are new cast-aluminium engine blocks with metallurgically bonded in-place cylinder liners, aluminium space frames and new Al-Mn alloys with higher levels of titanium. Bake-hardening steels are used increasingly in car body panels, with higher strength and improved dent resistance, and opportunities for weight reduction via downguaging (Bethlehem Steel Corporation). The Nippon Steel Corporation suggests that high-strength formable steel sheets with transformation induced plasticity (TRIP) will help steel compete against aluminium alloys, plastics and composites in terms of weight reduction. Also, vibration-damping steel sheet will find increased application in cars.

Advances in steel

Amongst new processing techniques introduced to meet greater microstructural control and international competitiveness are new vacuum melting and degassing techniques, once the province of stainless steels and aerospace alloys, now benefiting carbon and alloy steels, continuous casting, controlled rolling, and other thermomechanical treatments that reduce costs through reducing traditional heat treatments.

Near-net shape continuous casting of strip, rod and thin slabs will be given increasing emphasis as a means of enhancing competitiveness in the global market. There are also improvements in coatings for steel, together with induction heating processing, thus reducing energy costs and improving quality and yield. There is a search on for new cost effective high-temperature stainless steel alloys. Duplex stainless steels have been improving and are used increasingly in severe corrosion environments, and in chemical processing. Greatly improved steels and associated processing techniques aimed at better manufacturability in industry and enhanced performance in automobiles are shown below.

Improved steels for superior manufacturability

- New, highly formable steels:
    - vacuum degassed
    - interstitial free steels
- Improved uniformity/consistency
    - continuous casting
    - computer control of operations
    - improved thickness control
    - new annealing technologies
    - new surface roughness technology
- New prelubes

New steels for improved automotive performance

- Coated sheets →→→
  - — one and two side
  - — zinc and/or zinc alloys
  - — very uniform coating thickness
- High strength steels →→→ weight reduction and safety
  - — HSLA steels for structural components
    - -strength up to 200 KSI
    - -uniform properties
- Hybrid assemblies →→→ weight reduction
- Laminates →→→ noise control
- Coated steels for methanol fuels →→→ corrosion resistance

Source: P.T. Peterson and P.R. Mould, **The Plastics Trap**, September 1990, USS, Div. of USX.

High strength low alloy steels (HSLA)

HSLA steels are sophisticated mass-produced materials that enter the construction of large structures such as ships, oil platforms and cranes. By adding minuscule amounts of at least two metallic (such as niobium, aluminium, titanium, vanadium) and two non-metallic (such as carbon and nitrogen) components to the iron elements during hot rolling, a very fine grain structure is produced, conducive to high strength and good weldability. The extremely fine and stable distribution of tiny precipitates (about 50 atoms in diameter) prevent grain coarsening during heat treatment as in welding. This fine grain structure, which is effectively pinned down by carbide or nitride particles, gives rise to both high strength and fracture toughness[16].

To produce these desirable microstructures, appropriate processing techniques had to develop. Controlled rolling is one new important manufacturing technique used. The temperature during hot rolling is such that fine carbonitride particles can precipitate out, so that on cooking they prevent excessive growth of grains. Hence, the plate comprises the desired fine grain microstructure at recrystallisation at room temperatures, giving a strength of up to 600MN^{m-2} higher strength combined with high toughness, better low temperature properties and good weldability.

High-strength steel can also be produced if it is quenched rapidly from high temperature to ambient temperature which ,after tempering heat treatment, fine carbide particles precipitate, thus pinning down dislocations and grain boundaries.

HSLA steels provide opportunities for newly industrialized economies (NIEs) and other emerging economies with existing or planned steel capacity, summarised as follows[17]:

1. More effective utilisation of existing equipment capacity.
2. Production without licensing agreements.
3. Added-value for production.
4. Upgrading of local engineering standards.
5. Import substitution of costly heat-treated alloy steels.
6. Improved competitiveness in world export markets.

Superalloys

Advanced metals have generally been aimed at high-temperature, extreme conditions applications. Superalloys are nickel-based materials developed for just such uses. Nickel is melted down and mixed with aluminium and small amounts of chromium to impart anti-corrosive properties, and other metals such as titanium and tungsten for hardening. The superalloy is then cooled, to form a gamma-phase nickel-aluminium, and then further cooled in its solid state. Its resultant microstructure is such that dislocations cannot move easily, and so it is more difficult to deform. It is therefore harder than most conventional alloys. Nickel-based alloys become stronger at higher temperatures, peaking at 850°C but retaining useful strength up to 1,000°C. They are therefore used in compressor blades in gas turbine aircraft engines. Cobalt-based alloys retain their strength at much higher temperatures and are therefore used in the combustion chamber of the engine.

Superalloys have made much of our modern high temperature engineering possible. They form essential components of the gas turbines that power jet aeroplanes. In fact, it is these engines that have provided the technological pull for the development of superalloys. In addition to their use in gas turbines, they also serve in rocket engines and spacecraft, nuclear reactors, submarines, steam power plants, petrochemical equipment, and in corrosion resistant applications. Superalloys development flourished in the 1950s and 1960s. By the mid 1970s the main thrust came from tremendous processing improvements, and this has been the case up to now.

Despite these improvements, doubts exist as to the ability of nickel based superalloys to meet the future requirements in high-temperature applications, such as the gas-turbine. As conventional high performance metals are reaching their technological limits, even with new processing techniques, new materials are required for dramatic performance improvements required in advanced aerospace applications. Advanced ceramics and polymer matrix composites (PMCs) will be called upon to meet future requirements in advanced gas turbine and other applications, and this presupposes that they attain the same reliability as the metals they replace. Nevertheless, new advanced high performance metals will also play a significant role, and these include, metal matrix composites, aluminum-lithium and inter-metallics. The latter have great potential for high-temperature structural applications, replacing superalloys in high temperature sections of jet engines. Inter metallics are alloys possessing a highly ordered lattice or crystal structure as a result of processing technologies, such as rapid solidification. The most promising materials are titanium aluminides due to low density and high melting points, and nickel and iron aluminides. Inter-metallics is an important area in MSE today and some applications could come by the mid-1990s, while others only after the year 2000[18].

Rare earth minerals and metals

Rare earths are finding a growing range of advanced materials applications because of the unique properties possessed by individual rare earth elements. The major mixed rare earth oxide minerals are bastnaesite, monazite and xenotime, whose main constituent elements are lanthanum, cerium, preseodymium and neodymium, lending their properties to current applications in the glass, electronics, ceramics, chemical and metallurgical industries.

The major source of rare earths since 1979 has been bastnaesite, the production of which was around 47,300 tons (gross weight) in 1989, or nearly 60 per cent of the world output of rare earth minerals. It should be noted that Chinese production of rare earth minerals has been increasing by 20 per cent per year since 1989, with production capacity today exceeding 30,000 tons (contained rare earth oxide), of which 25,000 tons are of bastnaesite. Around 80 per cent of Chinese rare earth exports goes to Japan. Outside China, a major producer of bastnaesite is Molycorp in California (USA), with production of 23,3000 tons in 1989.

Yttrium is produced by Australia, China, Malaysia and Thailand as a by-product of tin mining. Australia also accounts for 45 per cent of the world output of monazite, which totalled 32,7000 tons (gross weight) in 1989. Monazite is derived as a by-product of heavy beach sand mining. The largest producer is Remison Goldfields, and if three new producers realise current plans to enter the rare earths market, the production of monazite by Australia would double by 1995. Nevertheless, Australia is the only major rare earth raw material producing country with no rare earth processing capability beyond the concentrating stage. A number of projects are under way to change this, including processing facilities by SX Holding Ltd., the China National Non-Ferrous Corporation, and China National Non-Ferrous Metal Import and Export Corporation (at Port Pine), and Currubin Minerals of Queensland and Rhône Poulenc of France (on the Gold Coast).

The value of the world rare earths market in 1988 was US$ 358 million (Japan 38 per cent, USA 28 per cent, Western Europe 18 per cent, other 20 per cent), with the largest markets being phosphors (43 per cent), magnets (16 per cent), glass polishing (10 per cent) and glass manufacture (7 per cent). In the USA the largest market, accounting for about 50 per cent, is for petroleum cracking catalysts, with metallurgical uses accounting for 20 per cent in 1989, ceramics and glass applications for 18 per cent, and other uses, such as electronics, phosphors, permanent magnets and ceramics, accounting for 12 per cent. In contrast, Japanese uses for metallurgical and petroleum catalysts requested only 5 per cent of the market, with magnets accounting for 20 per cent of the market.

World demand for rare earths is expected to increase by an average of 8 per cent per year through to the mid 1990s, with high purity rare earths spearheading this growth. The main area of growth will be magnets, where the neodymium-iron-boron magnets (see below) have replaced the samarium-cobalt magnets since 1987. From 1987-1989, Japanese production of neodymium-iron-boron magnets rose from 90 tons (11 per cent of the world rare earth magnet output) to 550 tons (46 per cent). Total market economy output is expected to rise to 10,000 tons by the year 2,000, with a derived demand for neodymium oxide of 5,350 tons. Neodymium comprises of 12 per cent of monazite and 20 per cent of bastnaesite, and the implied refinery production of neodymium oxide production from rare earth minerals in Australia, China and the USA is estimated at 7,400 tons per year, more than sufficient to meet demand projections.

Permanent magnets

An application of rare earths of major importance to industry is in rare earth magnets in electric motors, appliances, cars, printers and aerospace applications. The neodymium-iron-boron (Nd-Fe-B) magnet is much more powerful than existing samarium magnets and can lead to a reduction in the size of electric motors while increasing their efficiency.

Neodymium supermagnets

The rare earth element neodymium[19] is used in the new generation of permanent magnets. Neodymium belongs to the rare earth lanthanide group of elements. Over 95 per cent of existing permanent magnets are alnico or hard ferrite type magnets. Currently, the highest energy production of all existing practical permanent magnets is provided by the rare earth cobalt magnets. Nevertheless, there are indications that the new generation of supermagnetic materials, which have generated large international interest, could replace the ferrite, alnico and rare earth samarium-cobalt magnets.

Neodymium is derived from three main minerals, bastnaesite, monazite and xenotime, and constitutes about 17 per cent by weight of all rare earths mined. The main producers of rare earth minerals are to be found it in the USA, Australia, China, India, Malaysia, Russia, Brazil, Canada, Sri Lanka, Thailand, Zaire and Madagascar, in order of importance. Neodymium constitutes about 13 per cent of rare earth content, and the distribution of its reserves is shown in Table 9, indicating a 100 year life. (See also Table 10).

Taking advantage of the opportunities offered by neodymium in magnetic, colour glass, capacitors and laser applications, and of other rare earth elements in magnetic property applications and in advanced ceramic and glass, the technologies will doubtless involve familiarisation with a variety of complex extractive and processing methods for rare earths, including lengthy processing routes, such as metallothermic reduction and the new molten salt extraction process "Neochem" for neodymium. In addition, developing economies will need to employ RSP-PM (rapid solidification processing and powder metallurgy) technologies, as well as other more recent techniques, to produce the new range of permanent magnets based on neodymium.

Aluminium-lithium alloys

Traditional aluminium alloys in established aircraft applications are heavier than pure aluminium. It is known that the addition of lithium (with a specific mass half of that of water) to aluminium would result in a reduction of the density of the alloy. Earlier lithium alloys suffered from drawbacks, especially in terms of ductility and fracture behaviour. Nevertheless, once scientists demonstrated that aluminium-lithium-copper-magnesium-zirconium alloy systems could achieve both a density reduction of 10 per cent (and stiffness rise of 10 per cent) and toughness values, on an equivalent strength basis, to those of the already established aluminium-copper based aircraft alloys, then the way was opened for a new series of light-weight aircraft alloys. These alloys cover the property spectrum of the established alloys, but also have the additional advantage of a nearly conventional ingot metallurgy production route.

Table 9: Country estimated reserves

Country	Estimated Reserves (Kg x 10^3)
USA	650,000
India	400,000
South Africa	15,000
Central Africa	6,000
Malaysia	5,000
Brazil	5,000
China	4,600,000
Russia	70,000
Australia	8,000
Others	50,000

Source: N.C. Kothari, 1989.

LITAL alloys

The initial Al-Li alloy was patented by the Royal Aircraft Establishment, United Kingdom, for which Alcan has a worldwide licence, and is now internationally registered under the designation 8090. Depending on the processing path, it can be made suitable to substitute alloys such as 2015T6, or combining lower strength properties yet excellent fatigue and fracture behaviour, can be used in applications requiring durability and damage tolerance. Ingots of 8090 are now in routine production at the Alcan plate factory in Birmingham, UK, in weights of up to 3,000 kgs for the fabrication of plate, sheet, extensions and forgings. A second alloy in the aluminium-lithium-copper-magnesium-zirconium family has been patented by Alcan, internationally registered as 8091, intended as a high strength substitute for the high strength 7000 series aircraft alloys. Major Western aerospace manufacturers have already received development evaluations, trial and qualification amounts. LITAL alloys have now begun to be incorporated in the USA and the United Kingdom current aircraft projects. LITAL alloys offer designers a 10 per cent weight saving and improved stiffness, thereby increasing the potential weight saving in new designs by 15 per cent with very good fatigue properties.

Table 10: Role of rare earth and yttrium in advanced metals

Application	Material	Rare Earth or Yttrium Additives
High teperature High strength, high wear resistance material	Si_3N_4 SiAlON Z_vO_2	Y_2O_3 and Ln_2O_3
High strength ceramic	Ce_5 Y_2O_3	
Dispersion hardened	Al Ni Ti	Y_2O_3 Nd_2O_3 $E_{22}O_3$
Superconductor	Ba-Ca oxide	Y

Source: N.C. Kothari, 1989.

Alcoa and Al-Li alloys

Alcoa[20] has also been engaged in a lengthy R&D programme for the development, characterisation and widespread application of Al-Li products. Several problems not first envisioned in the alloy development stage had to be overcome in the last decade with important lessons learnt in fabrication, testing, materials characterisation and implications for design, and in determining correct property targets. An important conclusion seems to be that although Al-Li alloys have widespread uses, they cannot, in many cases, be directly substituted for existing aluminium alloys without detailed analyses of their different engineering characteristics, since the latter are critical to the design process. The current (1991) status of Al-Li Alcoa commercial status alloy products is given below.

Al-Li alloys – Alcoa Commercial Status

- Alloy 2090 – Committed to supply and service sheet
  } sheet
  } plate
  } extrusion
- Alloy 2091 – Committed to supply and service – sheet
- Alloy 8090 – Committed to qualifying and supplying plate as quickly as possible. Investigations underway for sheet, and a commercial position in 1990.

Al-Li alloy 2090 Alcoa product summary

Product Form	Temper	Characteristics	Status (1991)
Sheet	0	Annealed, lowest strength, maximum formability	Commercial
Sheet	T3	Good formability. Will approach T8X properties after ageing by user	Commercial
Sheet	T31	Moderate formability. Can be aged by T8X properties by user	Commercial
Sheet	T62	Solution heat treated and aged by user	Commercial
Sheet	T83	Strength similar to 7075-T6	Commercial
Sheet	T84	Strength/toughness similar to 7075-T76	Commercial
Plate	T81	Strength similar to 7075-T651	Commercial
Extrusion	T86	Strength similar to 7075-T6511	Commercial
Forging	T6E203		Development

N.B. Over 10 million lbs. ingot producing in 1989.

Current applications in production

Application	Market	Alloy/Product	Programme
Fixed leading edges	Commercial and military	2090 sheet 8090 extrusion	A330 – 340
Trailing edges	Commercial and military	2090 sheet 8090 extrusion	A330 – 340
Flooring	Commercial and military	2090 sheet extrusion	
Exterior surfaces	Space and military	2090 and 8090 sheet, plate	F/A18 X31A
Payload adapters	Space	8090 plate extrusion, forgings	
Primary structure	Space	8090 plate extrusion, forgings	

Advanced composite systems

There are two main points about advanced composite materials. The first is that they are the natural selection for use where extreme performance requirements cannot be met individually by monolithic materials. The second is that given that they can be tailored to meet specific needs, stress-strain distribution, temperatures and other conditions to be met in use, they will become the main structural materials of the future, displacing monolithic materials from many applications.

New technologies[21] are placing increasingly more stringent requirements for combinations of materials properties that no single material can meet. Nevertheless, mixing a matrix with a particular reinforcing agent can impart on the resulting composite material properties that neither material possessed on its own.

The first point to note is that materials perform better as particles or fine fibres, i.e. their useful strength is increased. The same is true of some organic polymers where polymer molecules are built as a long chain of carbon atoms. If these chains face the direction of stress the polymer is very strong and stiff. Aramid fibres are based on such a principle.

The next point is that composites are effectively strategies to synergistically combine materials so as to take advantage of the enhanced properties of fibres. For this, materials designers simply embed the fibres in a matrix of another material, so that the latter binds and protects the former. The reinforcing material contributes the main characteristics in terms of strength and stiffness, but the matrix also affects the properties such as heat and electricity conductivity. The combination of fibres and matrix govern mechanical behaviour. Figures 8, 9 and 10 show fibre and matrix combinations, (courtesy of the United States Office of Technology Assessment).

The determinant of matrix material choice is the temperature the material will face in use. Polymer matrices utilise thermoset plastics which cannot melt, or epoxies which are a thermosetting material. Clearly the choice made of the matrix will dictate how the material is processed and fabricated. For a polymer matrix composite (PMC) the process is long and labour intensive. The fibres in the form of yarns or bundles are impregnated with the matrix resin and are then assembled, mainly by hand or automated lay-up of many layers into a laminated structure. If the resin used is a thermoset the structure must be cured by a costly autoclave process, often held at high temperature for several hours. PMCs possess light weight and high stiffness and stress in the direction of the reinforcement, and they are therefore used in aircraft, cars and other moving structures. However, they decompose at high temperatures. Moreover, they are fabricated in a labour intensive, but increasingly automated process, which is not suitable for high volume, low cost industrial applications. Before they can be commercialised successfully costs must be reduced and the fabrication methods must be improved. PMCs are the most mature of the composite technologies. The least developed technologies are those of ceramic matrix. Metal matrix systems are between the two. In 1989, worldwide sales of PMCs reached US$ 4 billion, according to the United

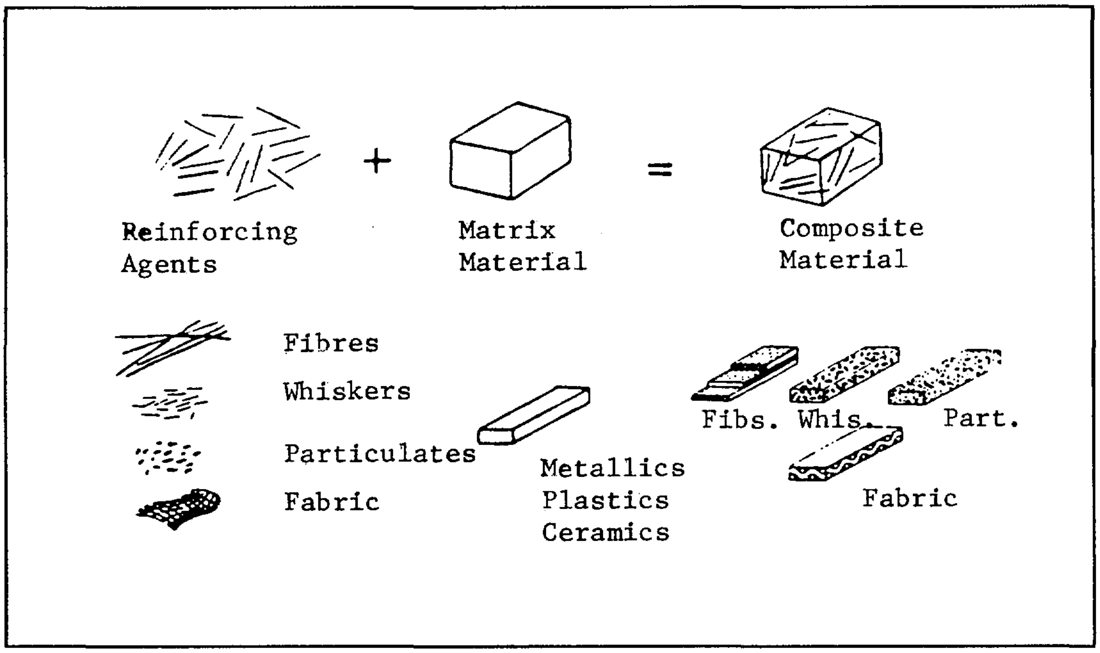


Fig. 8: Composite materials

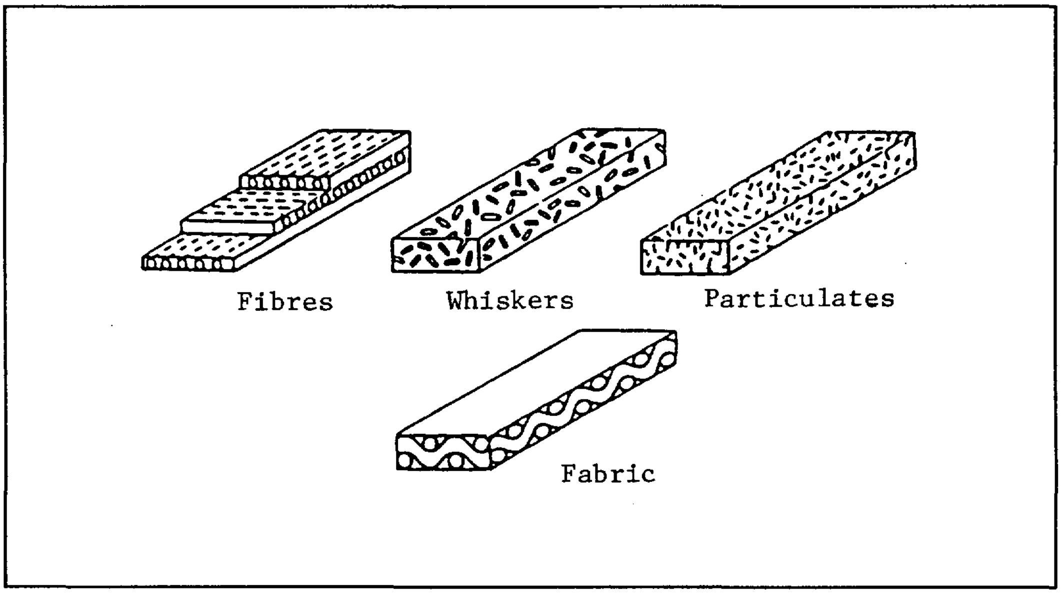


Fig. 9: Composite materials approaches

Continuous Fibres	Whiskers	Metal Reinforcements	Particulates (incl. flakes)	Metal Wires
Boron (B)	Over 100 materials produced	Iron (Fe)	Tungsten (W)	Tungsten (W)
Graphite (C)		Nickel (Ni)	Molybdenum (Mo)	Titanium (Ti)
Alumina (Al_2O_3)		Copper (Cu)	Chromium (Cr)	Molybdenum (Mo)
Silicon Carbide (SiC)		Nickel Aluminide ($NiAl_3$)	Silicon Carbide (SiC)	Beryllium (Be)
Boron Carbide (B_4C)		Aluminium Oxide-Alumina-Sapphire (Al_2O_3)	Boron Carbide (B_4C)	Stainless steel
Boron Nitride (BN)		Silicon Carbide (SiC)	Titanium Carbide (TiC)	Niobium-Tin (NbSn)-superconductor
Silica (SiO_2)		Graphite (C)	Aluminium Dodecaboride (AlS_{12})	Niobium-Titanium (NbTi)-superconductor
Titanium Diboride (TiB_2)		Silicon Nitride (Si_3N_4)	Tungsten Carbide (WC)	
Alumina-Boria-Silica ("NEXTEL")			Chromium Carbide (Cr_3C_2)	
			Silica ((SiO_2)	
			Alumina (Al_2O_3)	
			Molybdenum Disilicide ($MoSi_2$)	

Fig. 10: Reinforcing agents

States Aerospace Industries Association. Actual and forecast applications of advanced composites across market segments are shown in Table 11. The United States Office of Technology Assessment on the other hand points to a figure of US$ 20 billion annual sales for advanced composites by the year 2000. Such materials are critical for aerospace applications but will increasingly diffuse to civilian aircraft and possibly the car industry.

Table 11: Advanced composites market trends and forecasts

	1986	1988	2000	2015
World Growth:				
Volume (metric tons)	10,000	13,500	90,000	600,000
Value (millions US$)	800	1,000	10,000	30,000
Employment	20,000	25,000	200,000	500,000
By market (%):				
Aircraft/aerospace	55	44	50	40
Recreational	28	34	20	10
Industrial and other	17	22	30	50
By region (%):				
North America	58	60	55	50
Europe	23	14	20	22
Asia	19	26	25	28

Source: Suppliers of Advanced Composite Materials Association.

When temperature is high enough to degrade a PMC then a metal matrix is required. A metal matrix also supplements the strength of the reinforcing agent and its ductility enhances toughness. However, metals have high density in comparison to polymers (hence aluminium, magnesium and titanium are the commonest used) and offer severe processing difficulties. This is understandable since it is very difficult to surround fibres with metal. If the metal is molten then there may be interfacial reactions. MMCs possess unique characteristics that make them very attractive for many structural and non-structural applications, and in particular where control is required of physical properties, elevated temperature performance, improved wear resistance and weight savings are critical. The MMCs with the greatest potential are the powder metallurgy based aluminium matrix reinforced with particulates, whiskers and platelet of silicon carbide, and the liquid aluminium-based system reinforced with semicontinuous alumina fibre preforms. MMCs face several difficulties. The use of high cost raw materials and complex processing technologies result in significantly higher costs than competing materials. In addition, there is a tendency for the matrix-reinforcement bond to fail after repeated temperature cycles, and the interface can degrade due to reactions between the metal matrix and its reinforcement. Here again improvements in processing technologies are critical for greater diffusion of MMCs in the future.

For situations in which the matrix needs to be as heat resistant, light weight, stiff and strong as the reinforcing material, ceramics are used. In contrast to PMC and MMCs in which fibres are used to supply strength, in ceramic matrix composites (CMC) fibres block the growth of cracks and thus make the composite tough, since it is already stiff and strong given the ceramic matrix. A great merit of CMC is that it offers great temperature resistance. Many of them grow tougher and hence stronger as the temperature rises. This very property, however, makes for a difficult processing path. The process used is sintering, in which a ceramic powder is consolidated at high temperature and pressure.

Another composite is the carbon-carbon composite (CCC), which can tolerate the highest temperature of any known composites. Matrix and reinforcing agent are both elemental carbon. CCC retains most of its strength at 2,500°C, and is therefore used for the nose of space re-entry vehicles. This high performance composite is not as developed as PMCs, but is beginning to find greater use in military and civilian applications. There remain serious difficulties, however, that prevent faster commercialisation, such as the reliable reproduction of CCC components and oxidation resistance at high temperature.

The matrix material is selected on the basis of operating temperature, but reinforcing fibres are chosen on the basis of mechanical and chemical compatibility for the role ascribed to them. A prerequisite is that when the matrix is a molten fluid it must wet the fibre for adhesion.

A very important consideration is that the properties of a composite are shaped not only by the matrix and the reinforcing material, but also by the geometry of the reinforcement. This can be random of hardening a metal by small particles, but this does not enable one to control the orientation of fibres. Hence long fibres or yarns are used to strengthen high performance composites. Long fibres reinforce the composite more efficiently and their orientation can be subject to precise control. The internal structure of a composite can therefore be arranged in the most appropriate way, given the stresses it anticipates to encounter. Many possibilities exist to arrange the internal geometry. The central point is therefore that designers are able to not only control composition, but also the geometry of a material. However, to do this in order to produce the required product with the required properties necessitates theoretical modelling, understanding and prediction. It is a complex problem that is not yet fully resolved. For example, the strength of a composite needs to be described statistically because the ultimate strength of a composite is determined by localised defects.

Engineering design is being revolutionised because of the degree of control over properties that can be achieved in composite design. The design of a component and of the material are now a unified, simultaneous process. Materials scientists can tailor the microstructure of a composite according to the distribution of stresses it will be subjected to. But the very nature of its processing, its directional properties and forms given to it must come to be reflected in the shape of the component it comprises. Not only is it a merging of two formerly distinct activities, but it is enormously complex, requiring computerised modelling, testing and control with a large interdisciplinary team of designers and engineers. Moreover, it is tailorability that distinguished composites and laminate systems from other monolithic materials and will therefore lead them to dominate the materials markets in the early part of next century.

Alumina fibres[22]

Ceramic materials often exhibit their best properties in fibre form, because their strength and fracture properties are controlled by microdefects, which are introduced by the manufacturing process and therefore better control is obtainable in fibrous forms than in monolithic forms. Ceramic fibres enable the production of composites that possess most of the advantages of the ceramic, but without exhibiting their disadvantage.

The three main families of advanced fibres are carbon, silicon carbide and high alumina fibres. Silicon carbide fibres are available in a large variety but none has achieved commercial maturity. High strength carbon fibres have achieved commercial maturity in advanced composites (usually epoxy resin matrix) and total capacity in the world is around 5,000 te/a. Alumina fibres are available as stable or as multifilament continuous yarns. There are 12 currently available products and the most important suppliers are shown in Figure 11 and Table 12. Annual world production in 1990 is in Figure 12, and alumina fibre processes are shown in Figure 13.

Three Japanese companies entered manufacture of continuous fibres in the late 1970s. First Sumitomo, then Denka and very recently Mitsui Mining, have developed a pure alumina fibre similar to Du Pont's.

Apart from carbon fibres and glassy alumino-silicates, most other fibres are developmental. A stream of new fibres continue to be announced by Japanese companies. Many of the new products are very expensive (up to £800/kg) due to small-scale production. The cheapest fibres are stable products for the insulation market (£1-20/kg), continuous multifilament yarns cost form £50/kg (carbon fibres) to £400/kg ("Nicalon" silicon carbides fibre). Whiskers cost £150-300/kg.

Alumina Fibre Properties

1. Potentially cheap
2. Chemically inert at high temperatures (>1,000^{0}C) in oxidising or reduced atmospheres
3. Compatible with molten light metals and non-oxide ceramics.
4. Electrical insulator with low dielectric constant
5. Optically transparent/translucent
6. Fairly good mechanical properties (cold) maintained up to ca. 1,000^{0}C

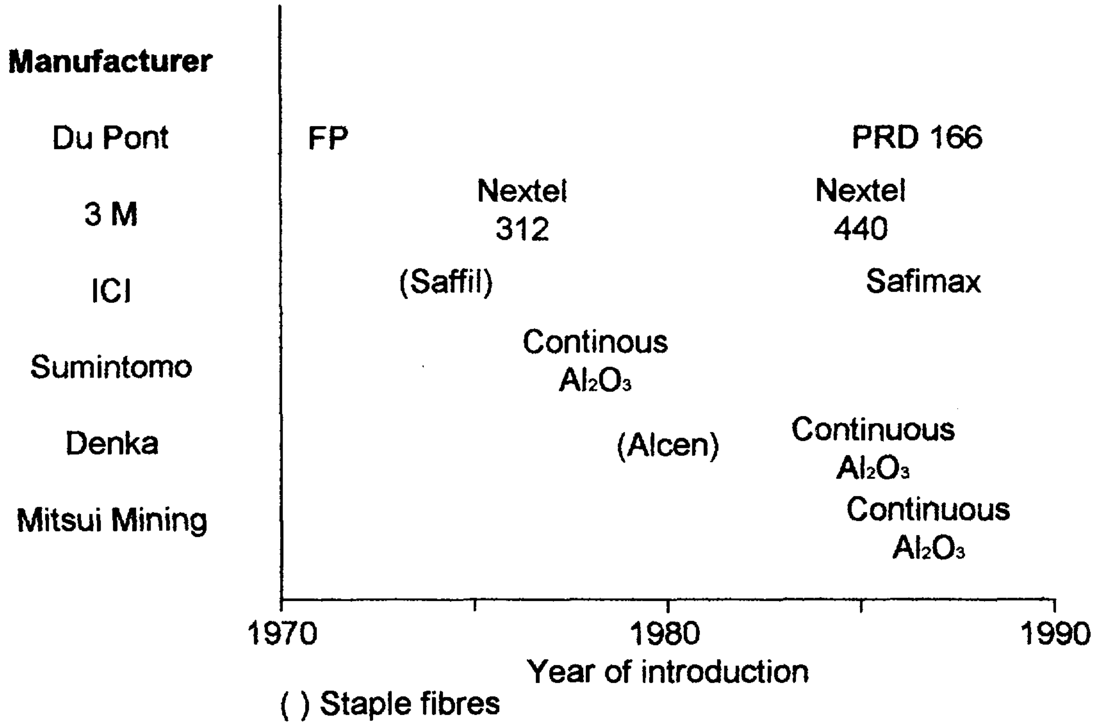


Fig. 11: Continuous alumina fibres under development

Table 12: Properties of high aluminium fibres

Manufacturer	**Fibre Name**		**Chemical Type**		**Form**	**Diameter μm**	**Length**	**Modulus GPa**	**Strength MPa**	**Density kg/m^3**	**Max use temp ^0C**
		% alumina	% silica	% others							
3m Company	Nextel 312	62	24	14% Boria	yarn (600, 900, 1200)	11	continuous	152	1,720	2,700	1,200
3m Company	Nextel 440	71	27	2% Boria	yarn (600, 900, 1,200)	11	continuous	207-240	1,720	3,100	1,370
Carborundum	Fibremax	73	27		staple	2-3.5	staple	150	850	3,200	1,650
Denka	Continuous	80	20		yarn (640, 880, 960)	10	continuous	200	1,500	3,200	1,250
Sumitomo		85	15		yarn (1,000)	17	continuous	200	1,500	3,200	1,250
ICI Plc.	Saffil Lt	96	4		staple	1-5	5 cms	200	2,000	2,000	1,100
ICI Plc.	Saffil RF	96	4		staple	1-5	5 cms	250	2,000	3,300	1,400
ICI Plc.	Saffil MA	96	4		staple	1-5	5 cms	250-300	1,500	3,400	1,600
DuPont	Fibre FP	>99			yarn (200)	20	continuous	380	>1,400	3,900	1,320
DuPont	PRD 166	80		60%ZrO_2	yarn (200)	20	continuous	380	2,070	4,200	1,400
Mitsui	Continuous	>99.5			yarn	10-15	continuous	350	2,000	3,900	n.a.

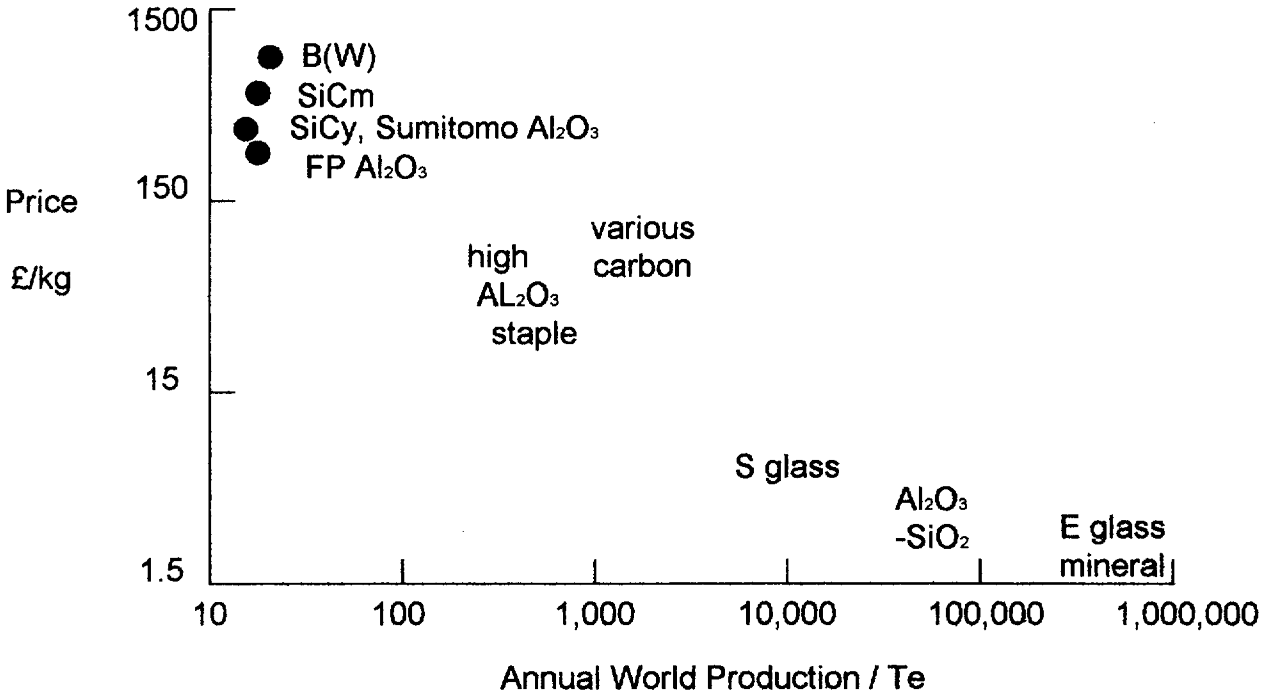
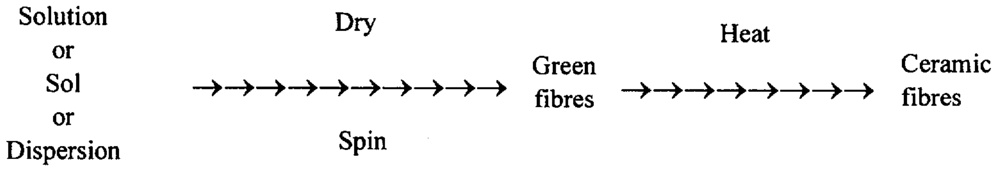


Fig. 12: Annual world production/Te



Examples:

1. Solution: Polyaluminoxane + polyethyl silicatae/benzene
2. Sols: Basic Al salt + silica sol water
3. Dispersion: Basic Al salt + 0.5μ αAlO_3/water

Improvements:

1. Rheology modifiers
2. Grain growth inhibitors
3. Reproducible raw materials

Fig. 13: Alumina fibre processes

Superconductors: ushering in a new age of technology?

At present we are in the midst of feverish international activity to translate the significant discovery, barely five years ago, of new high-temperature superconductors (HTS) into practical commercial application. It is widely recognised that this new family of superconducting materials has revolutionary implications for the technological and infrastructure foundation of our economies. Indeed, claims are being made that they will form the basis for a "new age of technology".[23]

Although it is difficult to exaggerate the potential applications of superconductivity, some of the claims seem to be erring on the side of wild exaggeration in terms of the time scale of application. Before superconductors can have a wide technological impact and diffuse throughout the productive structure of economies, they face considerable barriers in terms of processing and bulk production capabilities. That is, they must first be produced commercially into useful forms, such as thick and thin films, wire, tape and bulk materials.[24] The development of such fabrication and processing technologies may in fact require radical new technologies as the invention of the new superconducting materials themselves. While considerable advances have been made in this direction, much basic research and improvements remain to be done, with high returns for those corporations and economies with the research, development and manufacturing capabilities that will enable them to win the global race for the commercialisation of superconductivity. The importance of these developments has not gone unnoticed by governments in industrially advanced countries (IACs) and least developed countries (LDCs) alike. A concerted research effort is underway involving private laboratories, universities, and state support and funding. India,[25] for example, has set up a Cabinet-level committee under the Prime Minister to promote research on ceramic superconductors, and a Programme Management Body under Professor Rao, Director of the Indian Institute of Science and Technology, to coordinate the research at government and industrial laboratories, with a budget of several million dollars. Seven Indian research institutes are involved, such as the Tata Institute of Fundamental Research, and the National Physical Laboratory.

What are superconductors?

The phenomenon of superconductivity entails the complete disappearance of electrical resistance as a material is cooled below some critical temperature (T_c). The critical temperature is that temperature at which the material's resistivity abruptly changes from a state of normal electrical resistivity to a superconducting state.

Until the end of 1986 superconductivity was mainly connected with the properties of metals, e.g. niobium and alloys at temperatures around absolute zero (i.e. O°K on the Kelvin scale, where O°K= -273°C). But at these very low temperatures, only helium, with a boiling point of 4.2°K, is liquid and can be used in cryogenic systems. Even then a helium-based cyrogenic installation has itself to be cooled with liquid nitrogen (boiling point 77°K), making it an expensive, complicated and cumbersome system for machinery application.

It was in February 1987 that Professor Paul Chu of Houston University found that a new ceramic superconductor displays a T_c at a temperature of 94°K, well above the liquid nitrogen temperature of 77°K[c]. Amongst the new oxide materials that superconduct at temperatures around 90°K, the most well verified is the yttrium-barium-copper-oxide company, $YBa_2Cu_3O_7$, the so-called 1-2-3 with the highest T_c of 92°K, as far as we currently know.[26] In addition, another two classes of ceramic compound, bismuth and thallium oxides, have been shown unequivocally to superconduct at high temperatures.

Why is this discovery so important? First, note that superconducting materials cooled below their critical temperature allow electric current to flow with zero resistance, hence there is no power loss and no heating. Second, note that a material in a superconducting state is not penetrated by magnetic flux lines and can therefore repel magnets, what is known as the Meissner effect. The achievement of liquid nitrogen superconductivity was a major breakthrough introducing a new technology, since it lifted the constraints of very low temperature superconductivity requiring liquid helium as a refrigerant. Liquid nitrogen is much cheaper and operating temperatures can now be much higher, hence also reducing the complexity and cost of support, maintenance and operation of the cryogenic installation. Hence, the prospects for large commercial applications are very real and substantial.

The new superconductors operating above liquid-nitrogen temperatures can in themselves potentially transform technology[27], but the real breakthrough will come with the expected discovery of room temperature superconductivity. Such an achievement would truly revolutionise technology and lifestyles making available efficient and loss-free electricity and leading, for example, to compact small motors and actuators that can be incorporated in household consumer durables, cars, machine tool drives and power-packs to replace hydraulic systems of aircraft, and other unforeseen applications. Given that there is a lack of theoretical understanding of superconductivity for metals, and even more so for the new materials, we cannot predict the exact arrival of ambient temperature superconductivity. Nevertheless, some scientists have recently claimed that theoretical understanding of superconductivity in new materials at the atomic level may not be as necessary to progress in this field as hitherto claimed.[28] That is, the phenomenon may be too complex for it to be examined by mainly focusing on deducing macroscopic behaviour from microscopic assumptions, rather than looking at more intermediate-scale assumptions.

Table 13: Representative Applications of Superconductivity

LARGE SCALE PASSIVE

Shields, waveguides

Superconductors screen or reflect electromagnetic raduation; possible applications range from coating of microwave cavity walls to protect from the electromagnetic pulses of nuclear explosions.

Bearings

Repulsive forces created by exclusion of magnetic flux make non-contact bearings possible.

HIGH-CURRENT, HIGH-FIELD

Magnets

Medical imaging: LTS (low temperature superconductor) magnets widely used in fusion experiments and particle accelerators.

Scientific equipment: LTS magnets used in fusion experiments and particle accelerators.

Magnetic separation: Possible uses include separating steel scrap, purifying ore streams, desulphurising coal and cleaning up stack gases. At least one LTS magnet is in current use for purifying Kaolin clay.

Magnetic levitation: Levitated trains have been extensively studied, with prototypes in Japan and Germany.

Launchers, coil/rail guns: Electro-magnetic launching systems can accelerate objects to much higher velocities than gas expansions; possible applications range from small guns for military purposes to aircraft catapults and rapidly repeatable Earth satellite launching.

Other: Powerful magnets could eventually find a very wide range of uses. Examples: compact synchrotrons and lithographic processing of integrated circuits: growth of the crystals for integrated circuits (a strong magnetic field yields more nearly perfect wafers of silicon and other semiconductor materials); MHD (magneto-hydrodynamic) systems for energy conservation. MHD thrusters might also be used in place of propellers to drive ships and torpedoes.

Other static applications

Electric power transmission: Prototypes of LTS underground lines have demonstrated feasibility, but such installations are not cost effective (compared to overhead high-tension lines) at present.

Energy storage: Solenoids would with superconducting cable could store electrical energy indefinitely as a circulating current, in addition to utility applications (e.g. load levelling) superconducting storage. The military could find uses in military systems (e.g. pulsed power for surge lasers). Cheap and reliable superconducting energy storage would eventually find many other applications.

Rotating machinery

Generators: A number of LTS prototypes have been built to investigate possible electric utility applications.

Motors, motor-generator sets: Used in conjunction with a superconducting generator, a superconducting motor could be an efficient alternative to mechanical power transmission for applications such as ship and submarine drives, railway locomotives and perhaps even helicopters. Sufficiently low costs would open up many industrial applications.

ELECTRONICS

Passive: Superconducting wiring (interconnections) for computers, on-chip or between chip, could help increase processing speed.

Sensors: SQUIDS (superconducting quantum interference devices) made from Josephson junctions (JJs) are the most sensitive detectors of electromagnetic signals known; applications range from detecting neural impulses in the human brain to geophysical exploration, detection of submarines in the deep ocean from aeroplanes, or potentially from space, and non-destructive inspection.

Digital devices: JJs can also be used for digital switches, opening up such applications as computer logic and memory; competitive three-terminal devices with substantial gain may eventually be developed: combined semiconductor-superconductor devices or systems also hold many attractions.

Other devices: Analog/digital converters, voltage standards, many types of signal processors, and microwave mixers can all be designed, in principle, with superconductors; some of these applications (e.g. voltage standards) have been reduced to practice with LTS JJs.

Source: US Congress, Office of Technology Assessment, 1989.

More realistically, we should be looking at practical applications of liquid hydrogen cooled superconductors, given that nitrogen is both abundant and cheap. A recent US Office of Technology Assessment (OTA) report provides a useful summary of the potential applications of the new superconductors, shown in Table 13. It must be stressed however, that a concentrated large research effort is required over a period of five to ten years before many of these can be realised on a commercial scale. The new materials must be made sufficiently strong and flexible to be fashioned into useful forms and made capable of carrying large currents (over 100,000 per square centimetres at 77°K) and/or withstand large magnetic, gravitational and centrifugal forces (e.g. in spinning turbine generators). This research effort involving both engineers and scientists will be directed[29] at basic research to explain the phenomena and create new materials; applied research on processing methods; applications engineering for prototypes and testing; process engineering to develop manufacturing methods for mass production of cable and methods for inspection and quality control; and systems engineering for the design, development and demonstration of the integration of superconductor components into computers and electrical generation, for example. This long lead time provides an opportunity for engineers and scientists to focus their attention onto this area, to train a new generation of scientists, for government and corporations to commit resources in a long research efforts from laboratories and universities and to integrate the multidisciplinary requirements in knowledge, skill and experience ranging from physics, chemistry, electrical engineering, production engineering to materials science. In some developing countries this can become an integral part of a national science and technology infrastructure building, encompassing microelectronics and other advanced materials technologies, such as fine ceramics. It should be born in mind that in the medium term the greatest gains are economically to be found in small-scale applications of high temperature superconductivity, especially in various industrial machines and electronic devices. In the long run potential gains of interest to LDCs would include magnetic levitation trains for journeys between 100-600 miles, electric generation and, importantly, the ability to store massive amounts of electric energy with no energy loss, medical diagnostics (magnetic resonance imaging) and geophysical exploration. Finally, it should be clear that high temperature superconductors (HTSs) are essentially advanced ceramic materials, so that basic research and engineering capability in the two areas can reinforce each other.

Electronics, optics and optoelectronics

Materials for the processing and transmission of information

The central message of this section is that progress in the systems that process and transmit information is mainly dependent upon progress in materials science.[30] Electronic and photonic materials form the basis of systems of information and communication, and the ever increasing functional power of such systems. In order to achieve the present levels of functionality of microelectronics and telecommunications systems, it was essential that electric signals first be generated and transmitted and then controlled, amplified and switched. Each such improvement was achieved with the assistance of entirely new materials or improvements in processing technologies.

Optoelectronics

The information explosion and the need to communicate large amounts of data has led to the development of photonics, in which information is carried by pulses of light. The basis of this technology comprises a fibreguide of silica glass which transmits the emitted light pulses. This makes for a more efficient means of transmitting information via light pulses as compared to the pulse rate of electrical signals via a coaxial cable. The materials used are compound semiconductors such as indium gallium arsenide phosphide for the laser and ultrapure glass for the fibreguide. The materials in photonics correspond, although at a much higher scientific level, to the iron and copper used in electrical transmission at the end of last century. Already fibreglass has made substantial inroads in long distance telephone communications, as well as at the local level, and even in connections between and within machines. Progress in photonics has been very fast since the advent of the laser in 1958 and owes much to materials science and engineering, which has developed the compound semiconductors and ultra-pure glass to make it possible. For the advantages and applications of optical fibres see below.

By the late 1970s, optoelectronic technologies had penetrated public works, and optical communications, via digital optical transmission, today affect the lives of millions of people. In addition to optical fibre telecommunications, a second major growth industry spawned by optoelectronics is the optical disc industry, whose products can be classified by disc type (i.e. digital audio discs, video discs, CD-ROMs) and general purpose rewritable disc memories. Figure 14 provides projections for sales of the optoelectronics industry in Japan by 1993.

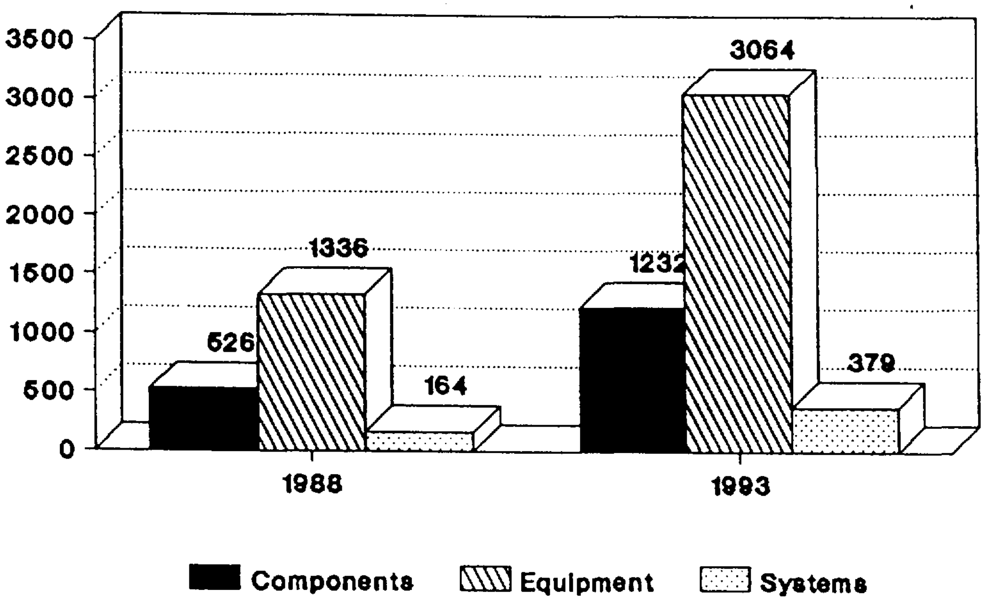
While photonics are on their way to replacing electronics in communications, in the area of information processing they remain at a "primitive" stage, akin to the position of electrical systems in their early formative years. A critical obstacle to the penetration of photonics in information processing machines is the absence of a commercially viable photonic control device which is equivalent to the vacuum tube, the transistor or the integrated circuit in electronic devices. Light signals can only be controlled, as yet, electronically, in the same way that electric signals could only be controlled mechanically before the invention of the vacuum tube. Nevertheless, there exist large commercial gains to be reaped by enhancing the functionality of photonic systems along the path already traversed by electronics.

Given that the major parts of the costs and materials used in an information or communications system are accounted for by the moving of electrons and photons from one point to the other, that is in the interconnections between the components of a system, be it within a single chip or across continents, costs rise as interconnections distance rises, and hence the materials required increase. Each interconnection of aluminium conductors linking circuit

Advantages and applications of optical fibres

Principal Advantages	Problems	Advantages of the Optical Fibre Solution
Large simultaneous transmission capacity, usually digital.	Electromagnetic perturbations (outsidr source). Example: cable parallel to an energy line.	No influence on the optical transmission; therefore no special protection shield is necessary.
Small, light, supple resistant cables (all of which have strong influence not only on the cost of laying and installing, but also on thecivilengineeringworkecessary for such a system .	Grounding problems: – lighting – NEMP	Metal free cables. No grounding necessary. Galvanic separations between transmission equipent.
Immunity to electromagnetic perturbations.	Combination of various source signals: – data – telephone – remote control – video – etc.	One lone cable for all possible kinds of information transmission. No crosstalk. It is no longer necessary to balance lines. Better possibilities to multiplex and combined signals.
No interference between parallel lines.	Very large capacity transmissions: – telephone – data – television	Very large bandwidth. Attenuation is independent of the electrical signal frequency.
Very slow signal loss, allowing the realisation of lines several dozen kms. long without amplifiers.	Long distance transmissions.	Low attenuation, thus few or no amplifiers.
Ease of cabling a large number of optical conductors together.	Laying of long lengths: – aerial cables – submarine cable –cables in ducts	Reduced laying cost. No line balancing, thus few junctions.
Optical fibres therefore solve several problems. **Overview**:	Little space: – indoor installations –computer networks –ducts already used by other cables	The smallest possible cable. Very light weight.
Applications Ranges Many areas are open to optical fibres, esp. in telecommunications:	Difficult laying conditions – small ducts – distant junction chambers	Low weight cables, therefore reduced pulling strength.

elements on a silicon chip costs about 10 millionths of a dollar. Each chip is mounted on a plastic or ceramic carrier with over a dozen metal leads, each lead costing a minimum of a cent. Chip carriers are mounted on large printed wiring boards, requiring a lot of materials, where the cost per interconnection rises by a factor of ten to 10 cents. Complex systems require several circuit packs (wiring boards filled with chip carriers and other circuit elements), which are interconnected to a large multilayer wiring board (the backplace) and linked to it electrically or optically. At this overall frame level the costs per interconnection rises to around one dollar. The cost of interconnecting frames between machines over long distances is very high and increases with distance. Increasingly, these connections are made via optical fibre, with users renting it as part of a national telecommunications network. Given the large part of total costs accounted by interconnections, the pressure is for miniaturisation of interconnections and the placing of greater and greater numbers of them on a single chip, and for advances in laser technology and optical fibre in order to reduce the costs of interconnections.



(OITDA)

Fig. 14: Forecasted sales of optoelectronics industry in Japan

Nevertheless, when taking into account progress in the size of chips that can be economically manufactured, new etching technologies, and reduction of defects due to automation of chip making and greater theoretical understanding, the limits to silicon technology can be reached in a few years.[31] At today's rate of progress, in which circuit complexity doubles every year, the number of components per integrated circuit can increase by a factor of fifty. The approaching ultimate limits of circuit integration on silicon would need to be resolved by new materials, such as gallium arsenide, or new designs such as dimensional chips. There are also limits to the pulse carrying capacity of the current laser and optical fibre technology. Silica-based glass fibres are already good enough and the objective is to reduce their costs. The move to repeaterless optical cables will need new fibre materials such as heavy metal fluorides. Insofar as laser technology is concerned, reaching its limits requires (a) the generation of much purer light; and (b) the ability to emit pure light at selected frequencies. At the same time, the ultimate limits in photonics depend on progress in electronics, since laser light pulses are triggered by silicon integrated circuits, which are capable of emitting about three billion pulses per second. Nevertheless, ultrafast circuits are required in photonic communication, and here compound semiconductors drawn from III-V of the periodic table are the best studied, and form the basis of lasers, light-emitting diodes and photodetectors.

Gallium arsenide semiconductors

After decades of mere promise as the technology of the future, gallium arsenide's[32] inherent advantages are finding applications in computers, television reception and optoelectronics, collaborating with rather than supplanting silicon. Gallium arsenide has the important property that electrons move through it at great speed. At equal or lower power, gallium arsenide circuits are faster than silicon circuits. Less power consumption means that this type of semiconductor generates less heat that must be drawn from the circuit. In addition to electron mobility, the compound's other major advantage over silicon is the greater ease with which the separation between its electronic bands can be engineered, thus facilitating more flexible transistor designs and versatile optoelectronic applications. A third major advantage over silicon is the ability to abdicate and detect near-infrared radiation. The resulting aluminium gallium arsenide or gallium arsenide phosphorous light-emitting diode (LED) can be found in tens of millions of electronic displays made every year. Moreover, gallium arsenide and its alloys can detect light by a process of reversing detectors, can respond faster than silicon ones, and can easily be integrated into high-speed electronic gallium arsenide circuits, such integration of electronic and optical functions offering major cost and functional advantages.

Nevertheless, serious constraints from the side of processing technology, together with advances in silicon technology, which still takes the lion's share in semiconductor research, have restricted its use to high unit cost niche applications where it possesses unique properties, as in front-end high speed receivers, in optical generation where there is no substitute material, and recently in digital circuitry applications in the highest-performing computers, as in supercomputer projects in Japan and the USA. It is, of course, in the field of photonic transmission of information that gallium arsenide is finding its major and growing application. Optical fibres are linking continents, telephone and cable systems, and are being used to extend the distance and speed of computer connections. Indium-gallium arsenide phosphide lasers are used for long distance communication because their infrared wavelengths cannot easily be absorbed by optical fibres. As computers are also becoming linked by optical fibres, low-cost optoelectronic devices will be needed. Such linking devices will need to eventually transmit data at one billion bits per second or more, which can, in principle, be achieved by either field-effect or bipolar gallium arsenide transistors. Despite the fact that advanced silicon bipolar transistors can also achieve this, gallium arsenide field-effect devices are now the technology of choice because less power is dissipated.

A photonics revolution in the 1990s?

We have seen that photonics has hitherto been a technology mainly applied to communications, its material foundations located in the II-V semiconductors. But in addition to the generation and transmission of photonic signals, there are enormous technical and commercial advantages to be reaped from photonic processing and control. For example, a photonics computer would possess much higher information processing capacity than its electronic counterpart. There are therefore strong pressures for the development of photonic control devices, which will do away with the high cost and complex conversion of light pulses into electronic form and back again. Although progress can be made with known naturally occurring compounds, advances in materials science and processing, notably molecular beam epitaxy, may lead to new families of materials with the desired optical properties and fabrication processes. The attainment of photonic control and processing capabilities will open the way for photonics communication systems, based on an all fibre network, the foundations of which are already being laid across continents, computers and homes.

In the USA, optical fibre systems operating at rates up to 1.7 gigabites per second connect nearly all long-distance routes, with capacity now being doubled to 3.4 gigabits (equivalent to 50,000 simultaneous telephone conversations on a pair of fibres). Fibre-based metropolitan area networks (MANs) are beginning to connect fibre based local area networks (LANs) networking computers and databases for business communications.

The final frontier to be conquered for an all fibre network, is the extension of fibre to the end user in the house. The introduction of the new digital format BISDN (broadband integrated services digital network) for integrating voice, data and image on the same line, necessitates that the fibre link terminates at home. In contrast to copper, optical fibre has the appropriate transmission characteristics to enable it to carry the broadband signals over long distances and to integrate the video, data, telephone and interactive database services, and indeed, the emerging video-based services fibre growth in residential fibre networks is expected to be rapid over the next decade or so.

In the 1970s and 1980s it was microelectronics that acted as the major driving force of the telecommunications and information revolutions. In the 1990s and early part of the next century, it is more than likely that it will be photonic transmission, photonic switching and photonic computing that will underwrite a new telecommunications revolution, moving us closer to "the ability to provide voice, data and images, in any combination, anywhere, at any time, with convenience and economy".[33]

The capability of photonic communications, measured as the product of the transmission rate (megabits/second) and distance in kilometres traversed before regeneration, is doubling every year and will continue for another 20 years before physical limits are reached. Coherent technology and optical amplifiers lie at the root of improvements in capability. But such high-speed photonic information must be converted, at present, to electronic format in order to be processed in electronic switching devices. Nevertheless, there is ongoing research effort pushing for a transition to photonic switching technology, using light instead of electricity to switch information. The self-electro-optic-effect-device (SEED) can control light with light, and was essential in the world's first photonic switch developed at AT&T's Bell Laboratories, comprising of an arrangement of lasers, lenses and symmetric SEED arrays on an optical bench. Moreover,[34] in January 1991, Bell Laboratories produced the world's first digital photonic processor. The use of VLSI technology can, in principle, be used to miniaturise and integrate optical components, ushering in a true transformation of the processing power of computers.

Optomechanics

Much is made in Japan of the fusion of major technologies which form the basis of spectacular technical progress. Microelectronics have been merged with mechanics and optics to form mechatronics and optoelectronics, respectively. Mechatronics refers to the incorporation of microelectronic devices into machines, thus enhancing precision, automation, flexibility and performance. Examples include numerically controlled machine-tools, robots, quartz instruments and home consumer durables. The manufacturing process in many heavy industries has been transformed, while this immense ability to process information is being incorporated not only in individual machines, but also in group technologies such as flexible manufacturing systems and factory automation. It is here that lasers, sensors and other processing technologies will become increasingly important. We have already discussed the role of optical fibres, laser and light-emitting diodes in the integration of light and electrons in the transmission and processing of information under optoelectronics. Developments in optical technologies based on laser technology, and their blending with mechanics, have resulted in optomechanics. The incorporation of laser beams into machines has resulted in hybrids which are quite different to traditional optical instruments, in such applications as advanced measuring instruments, processing systems, etc. Such machines, however, are currently controlled by microelectronics, hence all three fusion technologies are present, so that the term "optomechatronics" may be more appropriate. Laser technology clearly underlies all three fusion technologies. Table 14 shows the applications of the emerging field of optomechanics.

Table 14: Applications of optomechanics

Function Area of Application	Measuring	Processing	Information Processing
Machine tool	Ultra-precision measuring; In process measuring	Laser-applied processing equipment	
Industrial machinery	Robot with vision system; Assembly line with visual sensor; Tunnel excavator	Semiconductor manufacturing equipment Laser excavator	
Transportaiton equipment	Automobile traffic control system; Automobile collision prevention device		
Printing and office machinery			Laser beam printer; POS scanner; Copier; Laser disk file; Automatic photoengraving machine
Medical equipment	Automated analysis equipment; CT (computerised tomography) scanner; Optical instrument for opthalmologic treatment	Laser scalpel	
Aerospace-related equipment	Laser gyro; Fly-by-light; Remote sensing; Large-scale telescope		
Household appliances	Auto-focus/Auto-exposure camera		Video disk; DAD (digital-audio-disk)

Chemicals for electronics

For chemicals firms wishing to move downstream to higher value added niche markets, the electronics industry, with its demand for specialty compounded, purified and packaged chemicals, has been particularly lucrative – albeit difficult to satisfy its manifold and ever changing requirements and specifications. The types of process chemicals and the current and future use of process chemicals and inorganic and organic materials in electronics is shown[35] in tables 15, 16, 17 and 18.

Microcircuit fabrication requires process chemicals of ultra high purity and low particulate contamination. Therefore, chemicals suppliers to microcircuit fabrication engineers must provide prepackaged modules to insert in the processing equipment. A future trend is towards dry processing, so that the use of gaseous plasma etching is growing and more research is done on plasma developable resists. The ultimate aim is the full automation of a microcircuit fabrication track so that wafers are transported across dry processing chambers without human intervention or wet chemical contact. Higher purity and reproducibility in process chemicals is also a requirement in hybrid and printed circuit board manufacture.

In inorganic materials, the dominant material remains silicon, with 150 mm diameter wafers now the industry standard, and large scale manufacture concentrated in the hands of a few international suppliers such as Wacker in Germany, Shin-Etsu in Japan and Monsanto in the USA. Other materials include gallium arsenide in niche applications and glass as an optical fibre with surface diffusions to grade its reflective index and an outer polymeric coating for protection. Ceramics have been used largely as dielectrics in monolithic ceramic capacitors, as bulk piezoelectrics in transducers and as substrates (e.g. alumina for the fabrication of hybrid circuits). Interestingly, much research is currently directed away from bulk ceramics and towards the deposition of ceramics directly as thin films, thereby integrating them directly into microcircuit device processing technology. Given that such thin films are produced by sputtering, metallo-organic chemical vapour deposition (MOCVD) or sol-gel processing, this may diminish the demand for bulk ceramics and increase the demand for the chemicals needed for the thin film deposition processes. As Professor Ainger points out, this type of trend exemplifies an important characteristic of the use of materials in microelectronics: that is, the blurring of the demarcation between materials, process technologies and devices. This poses serious marketing and strategic problems for materials suppliers, since the material increasingly is formed *in situ* as part of device fabrication. To meet competitive and technological pressures, greater backward and forward vertical integration and collaboration between suppliers and users would therefore be in order.

Polymeric materials are used in a limited role (but major in terms of volume) in packaging and peripherals, e.g., in encapsulants, circuit boards and electronic equipment cases. But advances in packaging technology could lead to the utilization of polymeric materials in the form of glass fibre reinforced epoxy or engineering thermoplastics to produce plastic chip carriers. Already engineering thermoplastics are used for instruments, desk top computers, etc., but this will spread where machined or sheet metal cases are still used, e.g., in military systems, avionics and hostile environments (using fibre reinforced polymer matrix composites).

Table 15: Level of miniaturisation in electronic circuits and types of process chemicals used

Level 1:	Printed circuit boards with discrete components: transistors, capacitors, resistors, etc., soldered to a PCB.

Types of process chemicals

Solvents	Reagents	Etchants
Methanol	Hydrogen peroxide	Oxide techants
Xylene	Hydrochloric acid	Silox etchants
Trichloroethylene	Acetic acid	Polysilicon etchants
n-Butyl acetate	Ammonium fluoride	Silicon etchants
Isopropyl alcohol	Sulphuric acid	Contact etchants
Acetone	Nitric acid	Aluminium etchants
	Hydrofluoric acid	
	Phosphoric acid	

Source: Professor F. Ainger, 1990

But the most exciting and promising area is the active use of polymeric materials. Here the most prominent example of an electroactive polymer is polyvinylidenedifluoride and its copolymers, which are piezoelectric. Another is liquid crystals, which dominate the market for small displays, although they are moving into larger area displays and ultimately flat screen television. Ferroelectric liquid crystals and side chain liquid crystal polymers may become more important in the future. Other examples where much research is currently underway are electrically conducting polymers, photo and electrochromic materials, electro-optic and non-linear optical organics, both crystalline and polymeric materials. A potentially powerful capability is that of Langmuir Blodgett films, where molecular structures and molecular orientation can be tailored, together with control over film uniformity and thickness to molecular dimensions over large areas. This may lead to new generations of devices not possible from the use of inorganic materials today.

Chemicals firms, therefore, moving into high value added, high cost, research intensive specialities for the electronics industry face a cyclical, highly segmented, very competitive and overcrowded market requiring closeness to customers, product differentiation, and also requiring extensive technical sales servicing in order to assist electronics industry users to

Table 16: Process chemicals: current use and future trends

Application	Current	Future
Etchants, developers, solvent	Aqueous etchants, solution processing	Gaseous etchants, vacuum processing
Photoresists	UV wet developed	E-beam, X-ray resists, plasma developable resits
Degreasants	CFCs	CFC replacements

Table 17: Inorganic materials: current use and future trends

Application	Current	Future
Semiconductors substrate	Silicon	Silicon, II-VI, III-V
Piezoelectric Pyroelectrics Electro-optics	Bulk electroceramics	Thin film electroceramics
Optical communications	Glass fibre	Glass and polymeric fibre
Infrared windows	Germanium	Zinc sulphide Calcium lanthanum Sulphide

Table 18: Polymers and organic materials: current use and future trends

Application	Current	Future
Passive applications	Encapsulants	Plastic chip carriers
	PCBs	Integrated cases and circuits
	Metal cases	Composite cases
Active applications	Electro optic ceramics	Electro optic organics
	Inorganic thin film: - photochromics - electrochromics - piezo, pyroelectrics	Organic analogues
Display data storage	Liquid crystals	Polymeric LCs

incorporate the materials into product development and fabrication technologies. Not surprisingly, strategic alliances and cooperative agreements proliferate between electronics materials producers. An additional problem is the fast pace of technological change in semiconductors, so that chemicals firms barely have the time to recover the high R&D costs incurred. Moreover, it is difficult to predict major technology shocks making specific materials technologies obsolete, e.g., the development of high temperature ceramic oxide superconductors (which may lead to great demand for inorganic compounds such as yttrium, lanthanum, thallium, etc.), or optical fibres, or micro-fabrication technology shifts. Such research is done in the main within the R&D laboratories of electronics firms, and this makes chemical companies especially vulnerable to materials and technology shocks. Moreover, chemicals firms possess limited knowledge of device technology and normally become involved when the electronics industry attempts to move a technology from the R&D stage into production, and wants the chemical industry to supply the necessary starting materials. This then leaves them very vulnerable to unpredictable and/or radical changes in technology originating downstream. On the other hand, materials, especially precursor materials are closely connected to processing technology and device fabrication, while a device performance may critically depend on the development and application of advanced materials, e.g., liquid crystals in displays. Thus, chemicals firms must become involved in complex, expensive fabrication technologies they are not familiar with, either by moving downstream themselves to acquire in-house electronic device and fabrication capabilities, or enter into alliances with electronics users or other chemicals firms. Such comments apply with equal force to firms in other industries, e.g., steel firms in Japan, which have recently entered the electronics materials field.

Metallic materials for electronics[36]

Metallic materials have now been elevated to primary attention in semiconductor devices due to the increasing contribution of metal interconnects and electrodes to the functional performance of LSIs (large-scale integration) together with continuing progress in device miniaturization. From the 1960s, progress in integration technology has been fast, at 400 per cent every three years in memory devices, and is expected to continue at this rate until the year 2000. Microfabrication technology (photo-lithography and dry etching) and thin film technology will form the basis for the continuing progress in integration. Light wave will remain the exposiure media over the next decade in fabricating technology through the use of shorter wave lengths. In thin film technology, oxidation, CVD (chemical vapour deposition) and PVD (physical vapour deposition) techniques will be used, with control of single atomic (molecular) layer becoming a necessity in the future.

With the development of devices with higher speeds and levels of integration, current densities of interconnections must increase (over 1MA/cm^2 in the future), and this requires new matallic materials in place of aluminium. The present status, associated problems and prospects of metallic materials for LSI electrodes and interconnections is given below.

Current status and future prospects of metallic materials for LSIs

Current Status	Future
Electrodes: Low resistivity ohmic contacts	
Device speed has come to depend largely on the resistance of contacts. Low resistance achieved by increase in impurity contents as the surface layer of silicon, but this implies problems for future ultra shallow junctions.	Instead of conventional $\mathrm{P_tSi_2}$, the silicades $\mathrm{Ti\ Si_2}$ and $\mathrm{C_oSi_2}$ could be used as electrode materials.
Electrodes: Ultra shallow junctions	
Increasisng miniaturization of semiconductor devices has meant that junction forming techniques must continually evolve so as to produce the appropriate shallow junctions. Junction depth is 0.2µm Source/Drain in the current 0.5µ MOS device.	Junction depth will decrease to about 0.1µm in the future 0.2µm OS device. A prospective layered junction will be the structure $\mathrm{AlCu/W/TiW/(TiN)/TiSi_2(C_oSi_2)/Si}$.
Interconnections: Reliability	
To prevent a metallization failure due to electromigration phenomena, alloying elements such as copper, palladium and titanium in aluminium have been used, as well as, recently, multilayer interconnects [Al alloys/TiW(TiN, W)]. The problem of stress migration (SM) due to the mass migration of aluminium atoms due to differences in the thermal expansion coefficients can be prevented by alloying copper and palladium, but is not perfect.	A future problem remains the establishment of a complete method of SM reduction.
Interconnections: Resistivity of interconnects	
As the total length of interconnects increases due to progress in finer patterning and higher integration, the device speeds now depend strongly on the resistance of the interconnect lines.	Candidates for the substitution of aluminium include silver, copper and gold. Copper is the most promising as the next generation interconnect materials because of good matching with LSI processes, high resistance to EM and SM and low electrical resistance.
Interconnections: Multilayer metallic interconnects	
With progress in integration multilayered structures of metallic interconnects are required. Double multilayer metallic interconnects are now widely used.	In the near future, several (five to six) layer structures will be used in logic devices. Before such techniques can have wide application, it is essential that techniques for flat interlayer-insulators (planarisation) and via-hole filling must be developed. In future improvements and combinations of existing techniques (spin-on glass method, etch-back, direct planarisation with organic gas) will be combined with simulating films of low dielectric contact.

Metallic materials for sputtering targets: problems

1. Wide variety of materials: in addition to conventional materials, such as aluminium alloys, platinum, WSi_2, titanium and TiN, a wider variety of materials will be used, with likely candidates being tungsten, copper and cobalt.

2. High quality target materials: sputtering techniques are widely applicable to film formation, but problems of contamination due to particles and impurities exist. Hence it is necessary to improve the homogeneity of composition and microstructure and reduce the contents of radioactive elements such as uranium and thorium.

(Source: Summarised from Tokio Kato, Hitachi Limited, March 1991)

Magnetic materials for the recording media[37]

The dominant technology for the mass storage of information has been magnetic recording media based on particulate magnetic γ-iron oxide, but it faced limitation in achieving higher recording densities. This has led to a variety of magnetic thin film media (both metallic and oxide) being developed in order to achieve recording densities of near $10Mb/cm^2$. Modern information processing technology needs place ever greater demands on data and information storage technologies and their continual improvement. Mass storage refers to the on-line peripheral storage, usually the mechanical storage device as distinct from the solid state memory. Despite the continuous improvement in solid state memory in terms of informaiton bits per chip, peripherals will continue to be used for large scale data storage.

Magnetic data storage as the main technology for mass storage is now being challenged by optical data storage promising a density of >100 Mb/cm^2. Another challenger is the magneto-optic recording media, which uses an amorphous rare earth transition metal alloy thin film with a recording density as high as optical recording, but also erasable.

Progress in magnetic particles and coating technology has increased the recording capacity and lowered the costof magnetic tapes and disks now in use. Metallic thin film media are prone to wear and corrosion, but thin film of magnetic oxides may offer a promising intermediate solution. In the 1980s, many companies became interested in the technique of ‘‘perpendicular recording’’, utilizing at first a thin film of Co-Cr (cobalt-chromium) as the media (Table 17) This was thought to be a quantum jump over conventional recording, but more recent evidence shows that Co-Cr sputtered perpendicular recording is not much better than Co-P (cobalt-phsphorous) plated metallic media for longitudinal recording. Optical data storage techniques, which use laser beams to write/read encoded information at very high data rates and with extremely high densities are very promising (Table 18). Optical storage has a higher density of recording, needs a cheaper substrate and has a wider head gap, but it has a higher scale time and it is not erasable. Non-erasability has led to erasable optical memory with high recording density (using phase change thin film and magneto-optic thin film media), but they are rather unstable. Magneto-optic (MO) recording systems use a magnetic thin film in place of the ablating Te (tellurium) thin film used in optical recording. The most promising material is an amorphous alloy thin film of rare earth and transitional metal (TM). The rarer earth metals are gadolonium (Gd), terbium (Tb), dysprosium (Dy), or yttrium (Y) and the TAM metals are iron (Fe) and cobalt (Co). MO has certain disadvantages (table 19), but due to its erasability and capacity for large volumes of data, it is attractive for mass storage, especially in small computers as a replacement for present rigid and flexible disk storage. It is unsuitable for mainframe computers, because it is slow and easily oxidisable. Digital audio tape and digital video tape are developing very fast and will challenge the compact disk market.

Table 19: USA and Japanese companies making thin film media

Type of Film	United States of America	Japan
Plated metallic thin film media	Ampex Corporation, San Jose, CA Burton Magnekote Inc., Culver City Datapoint Corp., Mountainview, CA Eikon Inc., Simi Valley, CA Ibis System Inc., Duarte, CA Information Memories Inc., Santa Clara, CA KSI Disc Product Corp., Santa Clara, CA Media Tech. Corp., San Jose, CA Memorex, West Lake Village, CA Megastor, Chatsworth, CA Microdisk, Fremont, CA Polydisk Systems Inc., Torrance, CA Tandon Corp., Santa Clara, CA Ultra Disc, San Jose, CA Xerox Corp., Stamford, Conn.	Nippon Electric Company
Longitudinal thin film media	Eastman Kodak Co., Rochester, NY IBM, San Jose, CA Lin Data Corp., Santa Clara, CA Seagate Magnetics, Fremont, CA Trimedia Corp., Fremont, CA Varian Vacuum Systems, Santa Clara, CA	Fujitsu Ltd. Nippon Electric Co. Sumitoo Metal Mining Co.
Perpendicular thin film media	Eastman Kodak Co., Rochester, NY IBM, San Jose, CA Komag Inc., Milpitas, CA Lanx Corp., San Jose, CA Magnetic Peripherals Inc., Minneapolis, MA Microdisk, Fremont, CA 3M Co., St. Paul, Minn. Trimedia Corp., Fremont, CA Vertimag Systems, Minneapolis, MA	Anelva Hitachi Matsushita Electric NEC Sanyo Teijin

Source: Dr. B.K. Das, 1990.

Table 20: Available optical data storage systems

	Disc Dia. (cm)	Cap (GB)	Seek Time (msec)	Data Rate (MB/s)	Media
Fujitsu	30	1.0	350	2.4	-
Hitachi	30	1.3	250	1.5	Te alloy
Matsushita	20	0.7	300	5.0	TeO_x
Mitsubishi	30	37,400 frames	3,000	-	Metal film
NEC	30	1.3	250	6.5	-
Sanyo	30	18,000 frames	300	4.0	Te alloy
Sony	20	9,000 frames	-	1 – 5.5	Sb_2Se_3 + Bi_2Te_3
Toshiba	30	1.2	500	1.43	TeC
OSI	30	1.0	180	2.0	-
Optimum	30	1.0	160	-	-
Storage Technology	30	1.0	85	3.0	-
Thomson CSF	30	1.0	200	1.0	-

Source: Dr. B.K. Das, 1990.

Table 21: Thin film garnet material for MO recording

Agency	Material	Method
Philips GmbH	$Bi_{1.5}Y_{1.5}Fe_5O_{12}$ $(GdBi)_3(FeAlGa)_5O_{12}$	RF magnetron, sputtering
Philips GmbH	$(GdBi)_3(FeAlGa)_5O_{12}$	Selected area sputter epitaxy
Tokyo Institute of Technology	Bi,Al: YIG Bi,Al:GdIG $(Bi_2Y)Fe_{3.5}Al_{1.2}O_{12}$ $(Bi2Gd)Fe_{3.5}Al_{1.2}O12$	RF sputtering epitaxy and pyrolysis
Nippon Sheet Glass JPN	$(BiDy)_3Fe_{3.5}Al_{1.2}O_{12}$	Pyrolysis
Allied Corp., USA	$(BiYTGd)_3(FeGa)_5O_{12}$	LPE
Sumitomo, JPN	$(YbTbBi)_3Fe_5O_{12}$ $(GdBi)_3(FeAlGa)_5O_{12}$	LPE
Fujitsu, JPN	$(LuSmBi)_3(FeGa)_5O_{12}$	Flux-growth
Litton Corp., USA	$(BiTmY)_2Fe_5O_{12}$	LPE
Electrochemical Lab., JPN	Ca:YIG	LPE
IBM, York Town Heights	Gd:YIG & Eu: YIG	CVD
Masumoto, JPN	Fe-B-B, FeF, CoF, NiF	Sputtering

Source: Dr. B.K. Das, 1990.

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LIST OF ACRONYMS

A	Angstrom
A&E	Advanced and engineering materials
AER	Japan Atomic Energy Research Institute
AES	Auger electron spectroscopy
AIST	Agency of Industrial Science and Technology
AMPP	Advanced Materials and Processing Programme
ARPA	Advanced Research Projects Agency
AST	Agency of Science and Technology
ASTM	American Society for Testing and Standards
ATM	Asynchronous transfer mode
ATP	Advanced Technology Programme
BISDN	Broadband integrated services digital network
CAD	Computer aided design
CAM	Computer aided manufacturing
C/C	Carbon/carbon
CCC	Carbon carbon composite
CEC	Consulting Engineering Council
CFC	Chlorofluorocarbon
CIM	Computer integrated manufacture
CMC	Ceramic matric composites
CRADA	Cooperative Research and Development Agreements
CT	Computerized tomography
CTC	Civilian Technology Corporation
CVD	Chemical vapour deposition
DAD	Digital audio disk
DARPA	Defense Advanced Projects Agency
DOC	Department of Commerce (National Institute of Standards and Technology, NIST)
DoD	Department of Defense
DOE	Department of Energy
DOI	Department of Interior
DOT	Department of Transportation
DRAM	Dynamic random access memory

EADIE	European Association of Developmental Research and Training Institution
EC	European Community
EFTA	European Free Trade Area
EM	Electro magnetic
EOI	Export oriented industrialization
ERATO	Exploratory Research for Advanced Technology
EPA	Environmental Protection Agency
FCCSET	Federal Coordinating Council for Science, Engineering and Technology
GDP	Gross domestic product
GNP	Gross national product
HDTV	High definition television
HFSP	Human Frontier Science Project
HHS	Department of Health and Human Services
HIPs	Hot isostatic presses
HSLA	High strength low alloy steel
HST	Hypersonic systems
HTS	High temperature superconductors
IAC	Industrially advanced countries
IC	Integrated circuit
ICGEB	International Centre for Genetic Engineering and Biotechnology
IMAAC	International Materials Application and Assessment Centre
IMF	International Monetary Fund
IMS	Intelligent manufacturing system
ISDN	Integrated services digital networks
ITRI	Industrial Technology Research Institute
JETRO	Japan External Trade Organization
JIT	Just in time
JISEDAI	Research and Development Programme on Basic Technologies for Future Industries
JJ	Josephson junction
KAITECH	Korean Academy of Industrial Technology
KIST	Korean Institute for Science and Technology
LAN	Local area network
LCF	Low cycle fatigue
LPE	Liquid phase epitaxy
LDP	Liberal Democratic Party
LSI	Large scale integration

LTS	Low temperature superconductors
MAN	Metropolitan area network
MIT	Massachusetts Institute of Technology
MITI	Ministry for International Trade and Industry
MHD	Magneto-hydro-dynamic
MMC	Metal matrix composite
MNCs	Multinational corporations
MO	Magneto-optic
MOCVD	Metallo-organic chemical vapour deposition
MOS	Magneto-optic system
MRL	Materials research laboratories
MSE	Material science and engineering
NASA	National Aeronautics and Space Agency
NC	Numerical control
NEDO	New Energy and Industrial Technology Development Organization
NIEs	Newly industrializing economies
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NPL	National Physics Laboratory
NRC	National Research Council
NRIM	National Research Institute for Material
NSF	National Science Foundation
NSTB	National Science and Technology Board
OECD	Organisation for Economic Cooperation and Development
PEC	Petroleum Energy Centre
PMC	(1) Permanently manned capability; (2) Polymer matrix composites
PVD	Physical vapour deposition
R&D	Research and development
RSP-PM	Rapid solidification processing and powder metallurgy
SC	Steering Committee
SDP	Sputter depth profiling
SEED	Self-electro-optic-effect device
SEMATECH	Semiconductor manufacturers association (USA)
SHS	Self-propagating high temperature synthesis
SIMS	Secondary ion mass spectroscopy
SM	Stress migration

SOR	Spring-8 (Japan)
SPRU	Science Policy Research Unit
SQUIDS	Superconducting quantum interference device
SSC	Superconducting super collider
STA	Science and Technology Agency
STS	Supersonic transport systems
TM	Transitional metal
TPM	Total production management
TQM	Total quality management
TRIP	Transformation induced plasticity
TWA	Total working area
USBM	US Bureau of Mines
ULSI	Ultra large scale integration
UNCTAD	United Nations Conference on Trade and Development
UNCTC	United Nations Centre on Transnational Corporations
UNCSTD	United Nations Centre for Science and Development
UNIDO	United Nations Industrial Development Organization
USA	United States of America
USSR	Union of Soviet Socialist Republics
USDA	United States Department of Administration
VAMAS	Versailles Project on Advanced Materials and Standards
VCR	Video cassette recorder
VLSI	Very large scale integration
XPS	X-ray photoelectron spectroscopy

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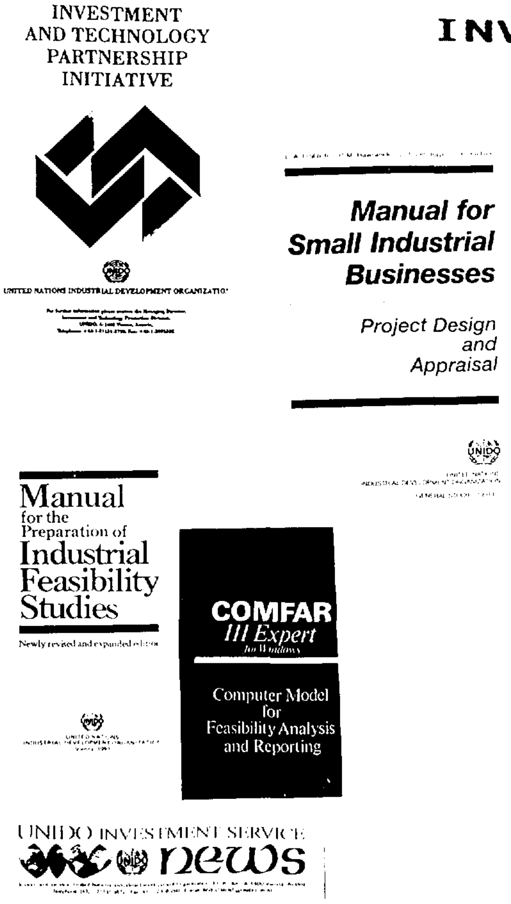

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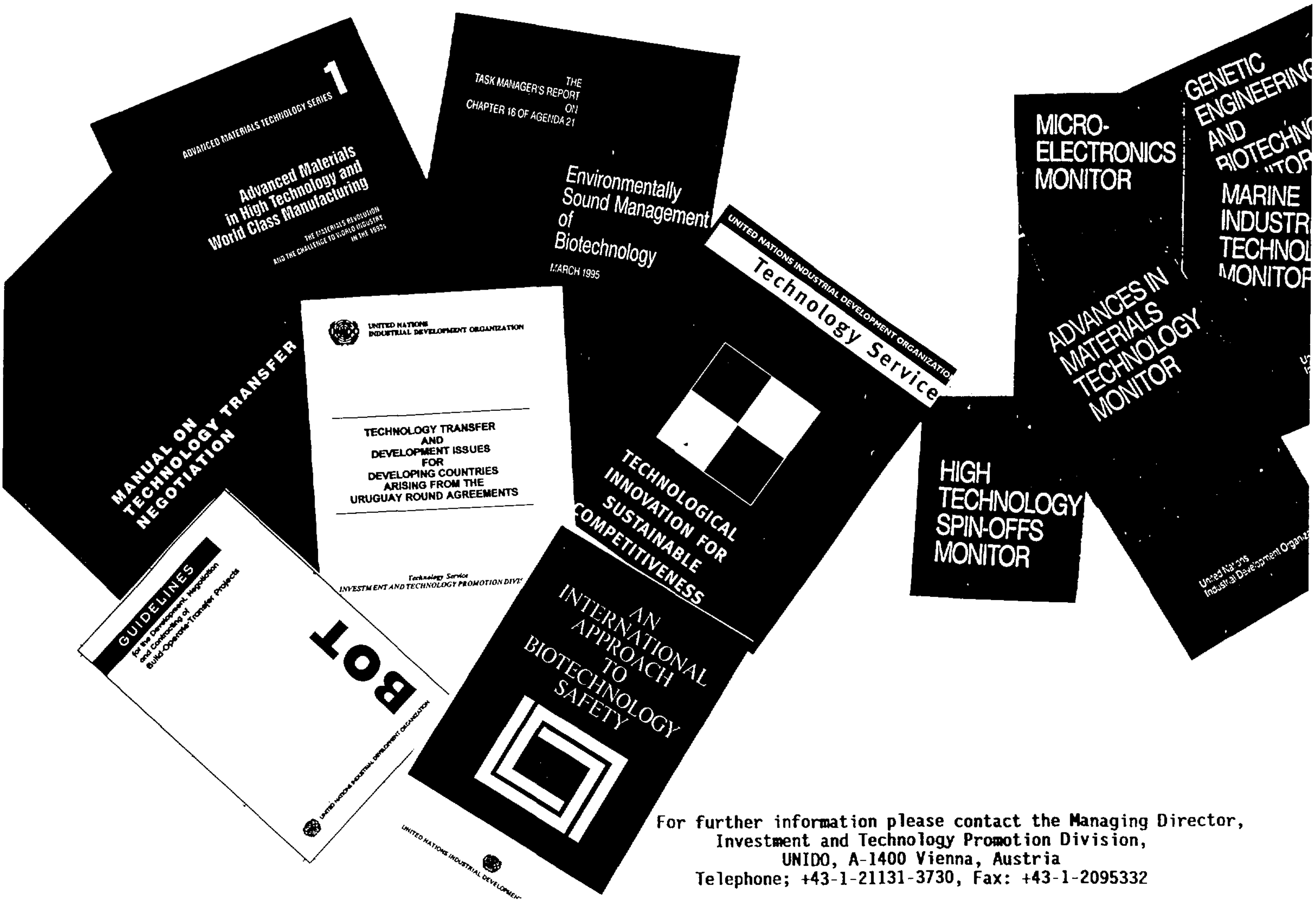

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