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## **Industrial and Materials Technologies: Research and Development Trends and Needs**

A Study for the Commission of the European Communities

by Prof. Dr. H. Czichos

in cooperation with Prof. Dr. R. Helms and Dr. J. Lexow

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## Preface

Technology is a vital factor for the economy of the European Communities. The completion of the internal market by 1992 must be supported by increased scientific and technological activities to improve efficiency and productivity throughout. In this context, industrial and materials research and development (R&D) plays an important role.

This study reviews the state of the art in this field and outlines priority areas for R&D activities. Industrial and materials technologies must be seen today in a systems approach as part of the "total product cycle": From raw materials processing, to the engineering of materials, the design and fabrication of products, its performance, testing and assessment and, finally, the disposal or preferably the recycling of waste. For a strategy to increase the value of products and engineering structures, R&D should result in materials and products of high consistency, quality and reliability, and with improved processability, performance and durability; besides that, environmental requirements must be met in the development and application of advanced materials and products.

The present report – which follows on from a previous study on Materials Research and Testing, published by Professor Czichos in 1982 – promises to be a valuable background document for the planning and performance of future-oriented R&D in industrial and materials technology.

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Director Technological Research  
Directorate-General for Science, Research and Development of the  
Commission of the European Communities



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## Summary

In this study, made on behalf of the Commission of the European Communities (EC) the present state of industrial and materials technologies, their basic technological needs and development trends in the EC are analyzed on the basis of a questionnaire enquiry and interviews with leading authorities and experts. The analyses show that industrial and materials technologies are of paramount technological and economic importance for the EC and can support industrial competitiveness through the application of novel materials, advanced design and manufacturing routes, and top quality strategies. Key industrially relevant goals and benefits include (i) costs-reduction, (ii) long-term performance, (iii) energy and materials savings, (iv) environmental compatibility, (v) recycling.

The following topics are headings of priority themes for future, medium-term R&D objectives:

### Technical area 1: Materials Technologies

- 1.1 Raw materials and recycling
- 1.2 Advanced materials
- 1.3 Optimization of materials properties for performance

### Technical area 2: Design

- 2.1 Design concepts for industrial products
- 2.2 Computer-aided design (CAD) and mathematical modeling
- 2.3 Integrated multi-sectoral concepts

### Technical area 3: Manufacturing

- 3.1 Manufacturing technologies for industrial products
- 3.2 Sensor-aided computer-and-human-integrated manufacturing (SCHIM)
- 3.3 Semi-finishing technologies

### Technical area 4: Testing and Assessment

- 4.1 Industrial metrology
- 4.2 Non-destructive testing (NDT) and quality control
- 4.3 Performance testing; assurance for products and processes
- 4.4 Standardization



# 1. Introduction: Industrial and materials technologies - an overview on status and general trends

It is generally recognized that industrial and materials technologies play a key role in the economies of all industrialized countries. The manufacturing industries provide in the main trading blocks, namely the United States of America, Japan and the European Communities (EC) around 28 %, 41 % and 28 %, respectively, of the Gross National Product (1988). For the EC, an overview on main industrial sectors by output and employment is given in Table 1.1 (Ref. 1.1).

Table 1.1 Overview on industrial sectors in the European communities by output and employment (1988)

Industrial sector	Output (billion ECU)	Employment (1000)
Building and civil engineering	412.6	8447
Chemicals	263.9	1678
Motor vehicles, parts and accessories	206.7	1815
Mechanical engineering	190.9	2344
Electrical engineering	187.8	2391
Manufacture of metal articles	145.5	2123
Production of metals	125.8	920
Textile industry	84.3	1548
Processing of rubber and plastics	80.7	981
Manufacture of mineral products	80.1	977
Computer and office equipment	39.9	239
Air transport	24.7	259
Instrument engineering	20.3	309

As indicators for the importance of the various sectors the following aspects may be considered:

- EC export rates to the world
- Product share of EC exports to the world.

In Figure 1.1 these indicators are shown for the following industrial sectors (Ref. 1.1):

1. Agricultural products, forestry, fishing
2. Ores and metals
3. Non-metallic minerals
4. Chemical products
5. Metal products
6. Machinery
7. Office and electronic data processing
8. Electrical products
9. Motor vehicles
10. Other transport equipment
11. Food, drink and clothing
12. Textiles and clothing
13. Leather and leather products
14. Wood and furniture
15. Paper and printing
16. Rubber and plastics
17. Other products

According to Figure 1.1, the industrial sectors as characterized by their importance to EC trade can be allocated among three levels which may be called "very important" (VI), "moderately important" (MI), and "less important" (LI). The sectors which are currently of dominating importance are:

- Chemical products
- Office and electronic data processing
- Electrical products
- Motor vehicles
- Machinery

Because of the impact of the various products and technologies there is great concern in all industrialized countries to maintain or to increase the competitiveness in industrial sectors through technological improvements and innovations. According to a study of the organization for Economic Co-Operation and Development (OECD) on "New Technologies in the 1990s" (Ref. 1.2) for a technology to have pervasive economic effects and employment implications it must:

- (i) Generate a wide range of new products and/or services,
- (ii) Have applications in many sectors of the economy,
- (iii) Reduce the costs and improve the performance of existing processes, products and systems,
- (iv) Gain widespread social acceptance with minimal opposition, leading to a favourable regulatory framework,
- (v) Generate strong industrial interest based on perceived profitability and competition advantage.

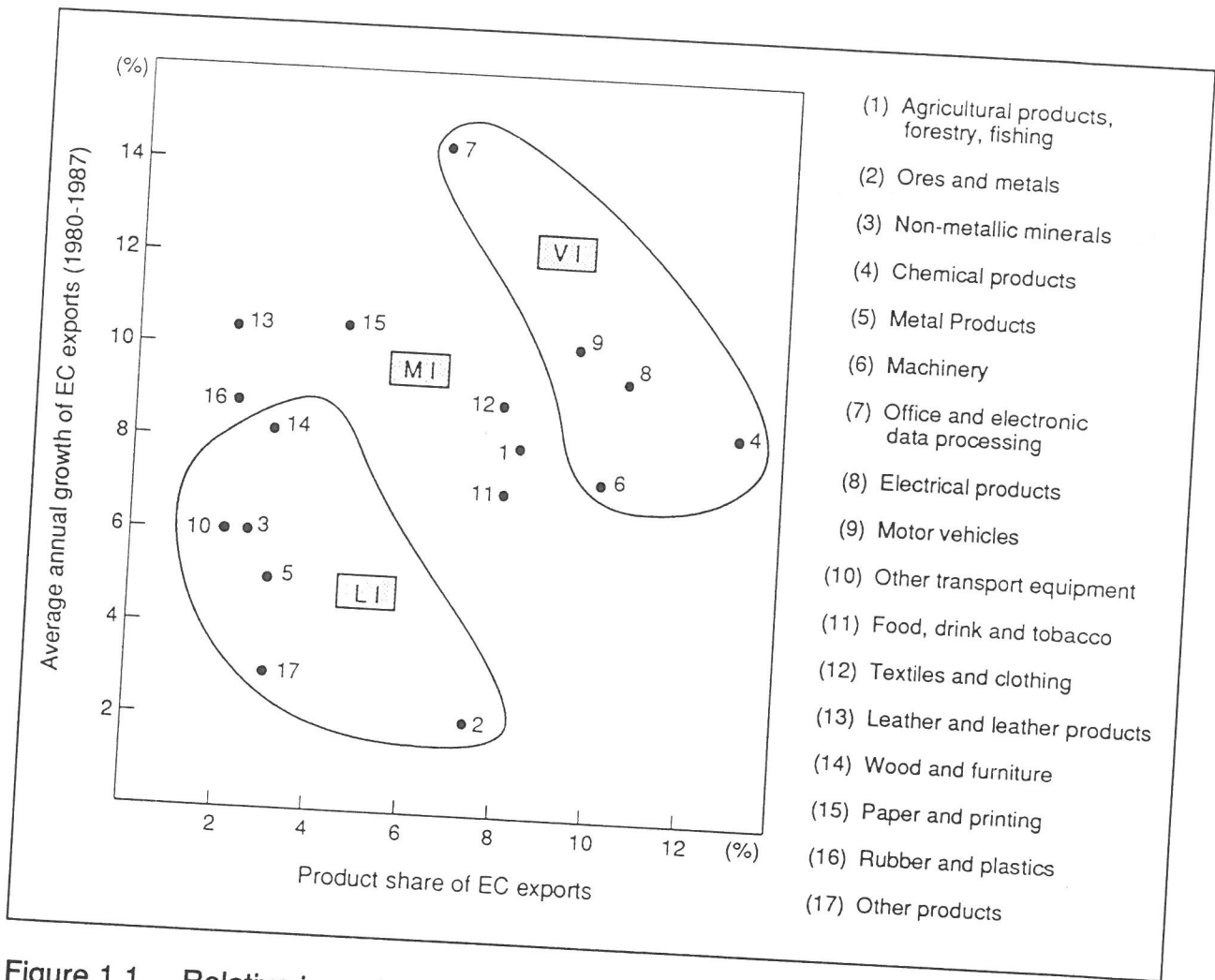


Figure 1.1 Relative importance of product sectors for EC exports to the world (1987)

In this context, materials technologies play a crucial enabling role (Ref. 1.3) for industrial components and products, and their design and processing in the following main aspects:

(a) Structural components and products:

Structural components are the elements of any technical product or engineering system subject to mechanical or mechanical/thermal loads and stresses. There is a continuous need to improve and to develop new structural materials, especially in the following sectors:

- In the engineering industry and robotics through new equipment and processing technologies, e.g. welding, assembly, bonding, use of laser
- In the car industry by means of steel improvement, the substitution of metals by plastics and attempts to lighten vehicles
- In the aerospace industry where composites are making progress and where the outlook for certain alloys, for example aluminium/lithium, seems promising
- In housing, because of beneficial properties of advanced materials with respect to heat insulation, anti-vibration or mechanical stability
- In the health sector where bio-materials as implants or prostheses are increasingly important
- In the sport and leisure industry

**(b) Functional components and products:**

Materials play in advanced industrial sectors an enabling functional role when their performance standards are very high in a certain area or when they provide a range of useful properties, especially of electrical, magnetic or optical nature. They are then often the key to new technical systems such as silicon semi-conductors in the electronic field, glass fibres for cable telecommunications, rare earths for magnets or optical applications and ceramics for combustion engines and sensors.

**(c) Design:**

Progress in materials developments enlarge the portfolio of available choice to the industrial designers and enable the most desirable qualities and attributes to be chosen at an early stage. This "customising" of materials is closely associated with the introduction of computer-aided design (CAD) and other information technologies.

**(d) Processing:**

The large number of contemporary methods of treating and processing advanced materials - for example reactive or injection moulding, extruding, stamping, superplastic forming, ultra-rapid solidification, powder metallurgy, sol-gel methods, vapour deposition, epitaxy - affects the market for equipment needed to produce the corresponding parts. The possibilities of robotizing and computerizing their production adds further to the range of possible applications.

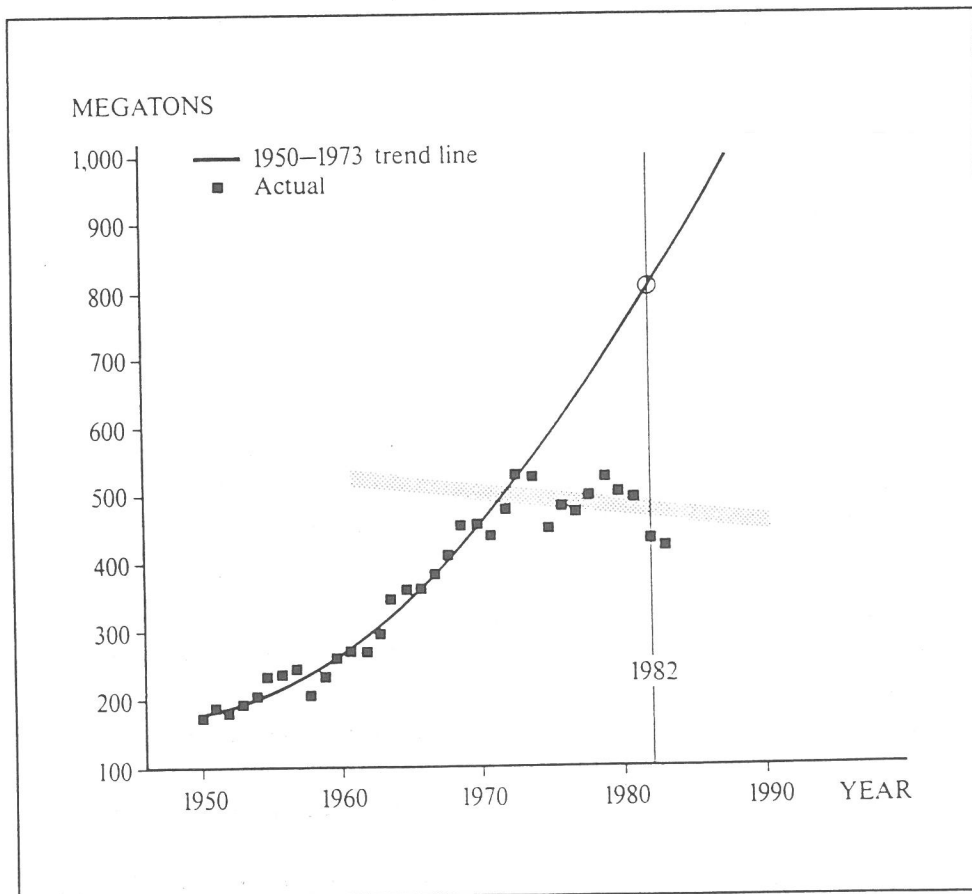


Figure 1.2 Steel consumption in the Western world



Table 1.2 World mineral reserves of basic materials and consumption rate changes

Commodity	World reserves (10 <sup>6</sup> tons)			Annual consumption rate change (%)			
	1972 <sup>a)</sup>	1986 <sup>b)</sup>	1990 <sup>d)</sup>	average 1972 <sup>a)</sup>	1974-79 <sup>c)</sup>	1979-83 <sup>c)</sup>	1983-87 <sup>e)</sup>
Bauxite (Al)	1170	21034	21589	6.4	3.0	- 1.1	3.1
Copper	308	337	328	4.6	3.5	-1.9	1.2
Iron	100000	65502	65321	1.8	0.1	- 1.4	2.5
Lead	91	87	75	2.0	4.4	- 1.9	2.0
Nickel	66	44	49	3.4	1.9	- 2.3	...
Tin	4.3	3.2	4.3	1.1	-0.8	- 2.0	-0.3
Zinc	123	148	156	2.9	1.1	-0.8	2.5

a) Club of Rome, Meadows, 1972  
b) ATAS Bulletin 5, 1988, p.25  
c) ATAS Bulletin 5, 1988; p 64  
d) Bundesanstalt für Geowissenschaft und Rohstoffe, 1990  
e) Statistisches Jahrbuch der Bundesrepublik Deutschland 1987 and 1989

With respect to possible trends in industrial technologies there are two general dimensions to be considered (Ref. 1.4):

- (i) Increased efficiency of material use and substitution by new materials can cut heavily into the demand for conventional minerals and metals. Consider, for example, the Western world steel consumption over the last three decades, which was only 50 percent in the 80's as compared with the expectations based on an extrapolation of the actual consumption in the years 1950 to 1973, see Figure 1.2 (Ref. 1.5). The pessimistic predictions made by the Club of Rome in 1972 in its study "The Limits of Growth", namely that existing deposits of industrially important metals for example lead and zinc would be exhausted by the year 2000 turned out to be false. Today, almost 20 years later, no shortage of any mineral resource can be foreseen for several decades to come (Ref. 1.6). Table 1.2 gives an overview on world reserves of some basic minerals, indicating an increase in some resources and a general decrease in consumption rates.
- ii) The second dimension of new materials technologies relates to the opportunities being created for new products and substitutes. Advanced materials form the basis for almost all new industrial products - from optoelectronic equipment and sophisticated sensors to high-density data storage and advanced semiconductor devices. Projected sales figures of some "high-tech areas" for the year 2000 in the USA are shown in Figure 1.3.

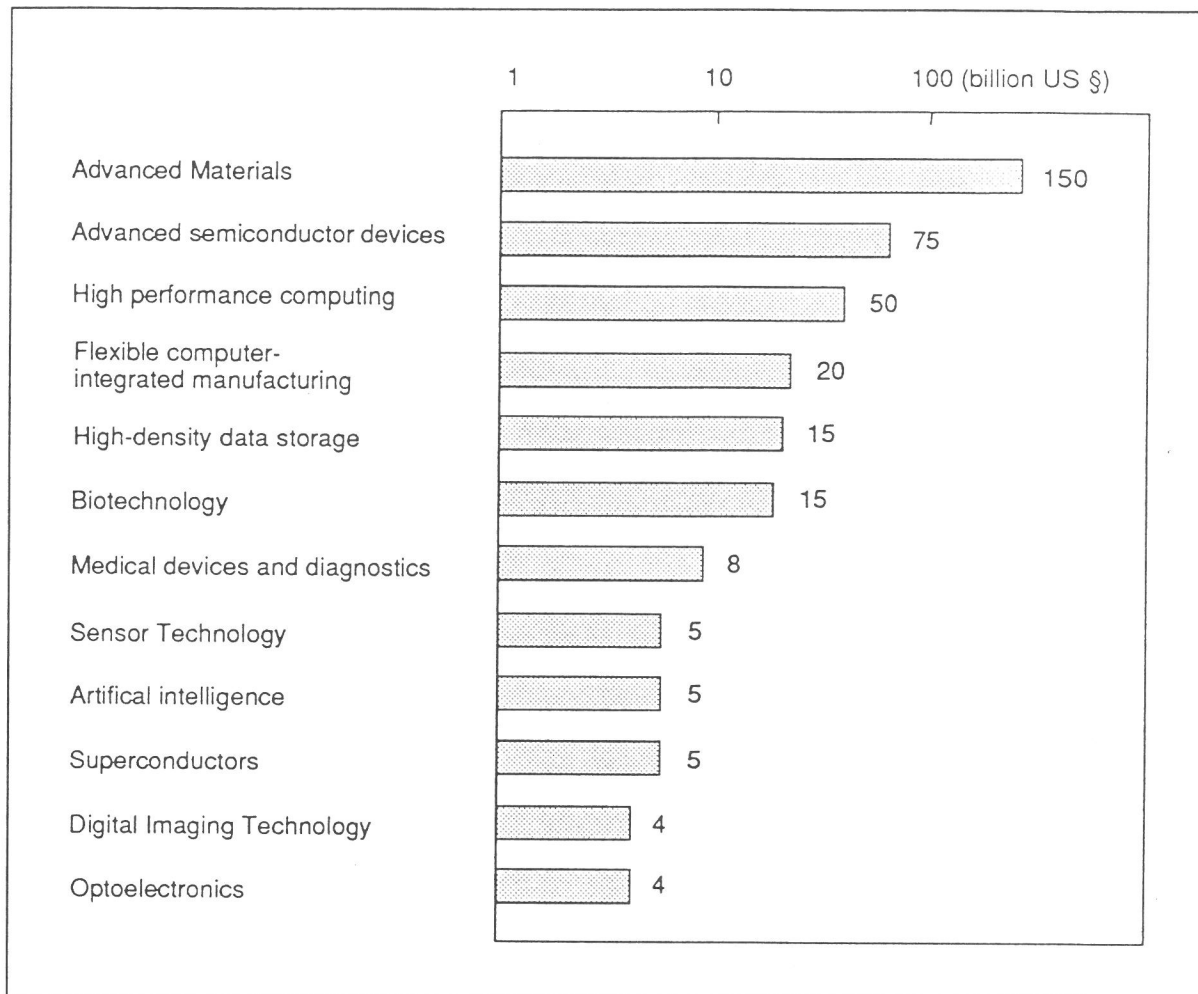


Figure 1.3 Projected US sales figures in high-tech sectors for the year 2000 (\$356 billion) (Source: US Department of Commerce)

The introduction of new materials and the further development of conventional materials lead to changes in most industrial sectors. The changes taking place in the automobile and aircraft industries are perhaps the most noteworthy because of the future implications.

The changes in materials use in US passenger cars in a period of 10 years is given in Table 1.3 (Ref. 1.5). It is readily seen that, generally speaking, iron and steel are being increasingly replaced by plastics, composites and aluminium. In this connection it should be noted, however, that although the proportion of iron and steel is decreasing in total, the percentage of the share of high-strength low-alloy (HSLA) steels is increasing (see Section 2.3.1).

Trends in materials applications for commercial aircraft structures are shown in Figure 1.4 (Ref. 1.5). It is anticipated that by the year 2000, fibre-reinforced composites or possibly aluminium-lithium alloys will have replaced most of the today's conventional alloys in aircraft structures.

Table 1.3 Changes in materials use in US passenger cars in a period of 10 years

Material	1976	Kg per car 1986	Growth rate (% / year)
Iron and steel	1278	1010	- 2.4
Plastics/composites	73	97	+ 2.9
Aluminium	38	63	+ 5.0
Glass	39	38	0
Others	262	217	- 1.9
<b>Total</b>	<b>1692</b>	<b>1426</b>	<b>- 1.7</b>

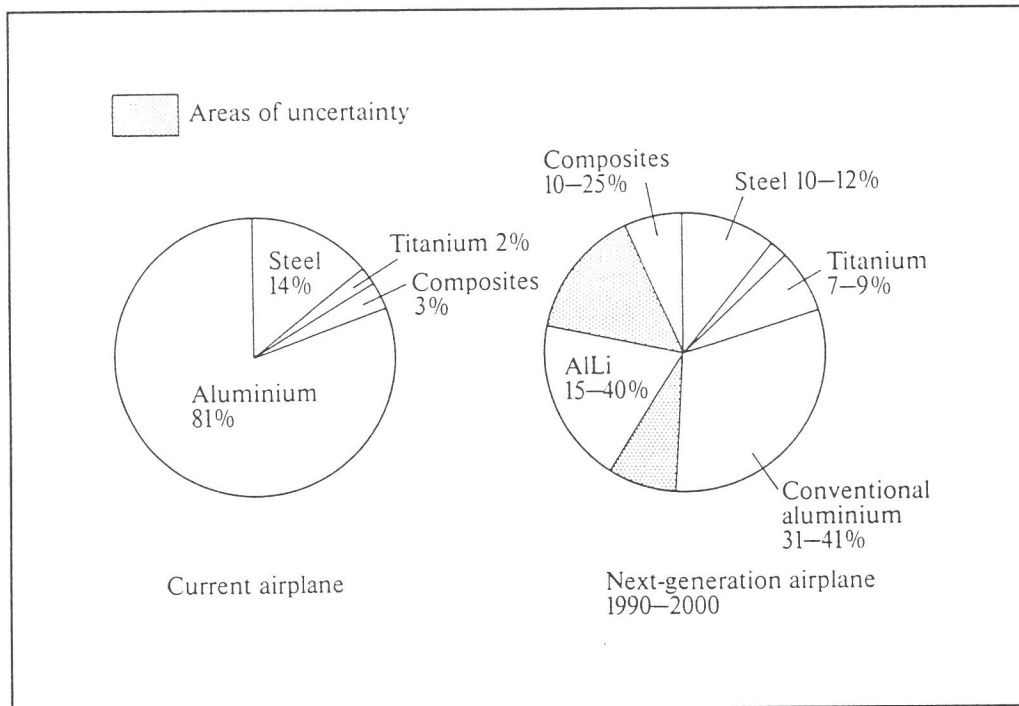


Figure 1.4 Trends in materials use for commercial aircraft

A global world market outlook for new materials by product categories and industrial sectors has been attempted in a recent French study (Ref. 1.7). According to Table 1.4, new or improved steel products account for half of all new materials with expected average annual growth rates of about 2 percent. Ceramics, which account for only one tenth of the total sales have an expected growth rate which is about four to five times higher than that of steel products.

Table 1.4 New materials market (1988), breakdown by material type

New materials	Market (GF)	Annual growth 1988-1995 (%)
New steel	365	+ 2.8
Technical thermosets	123	+ 4.9
Materials for electronics	119	+ 12.0
Non ferrous metals	107	+ 2.8
Composites	99	+ 8.9
Technical thermoplastics	90	+ 8.7
Ceramics	60	+ 11.9
New glass materials	39	+ 9.6
Total	1002	+ 6.5

The new materials compiled in Table 1.4 are used in the following sectors in Europe (Ref. 1.7):

- Automotive..... 24 %
- Electronics - Electrical industry..... 18 %
- Mechanical industry..... 18 %
- Building industry..... 16 %
- Packaging..... 8 %
- Sports and leisureware..... 3 %
- Aeronautics..... 2 %
- Miscellaneous..... 11 %

The different sector's relative positions change if we examine growth rates of new materials use, see Figure 1.5. Packaging, aerospace engineering, automobiles, and sports and leisure have the highest consumption growth rates, and packaging has the very highest. The high expected growth rate for new materials use in this sector is due, not to an increase in production, but to an expected rapid change in the materials used by this sector. Construction, on the other hand, has until now been slow to adopt new materials.

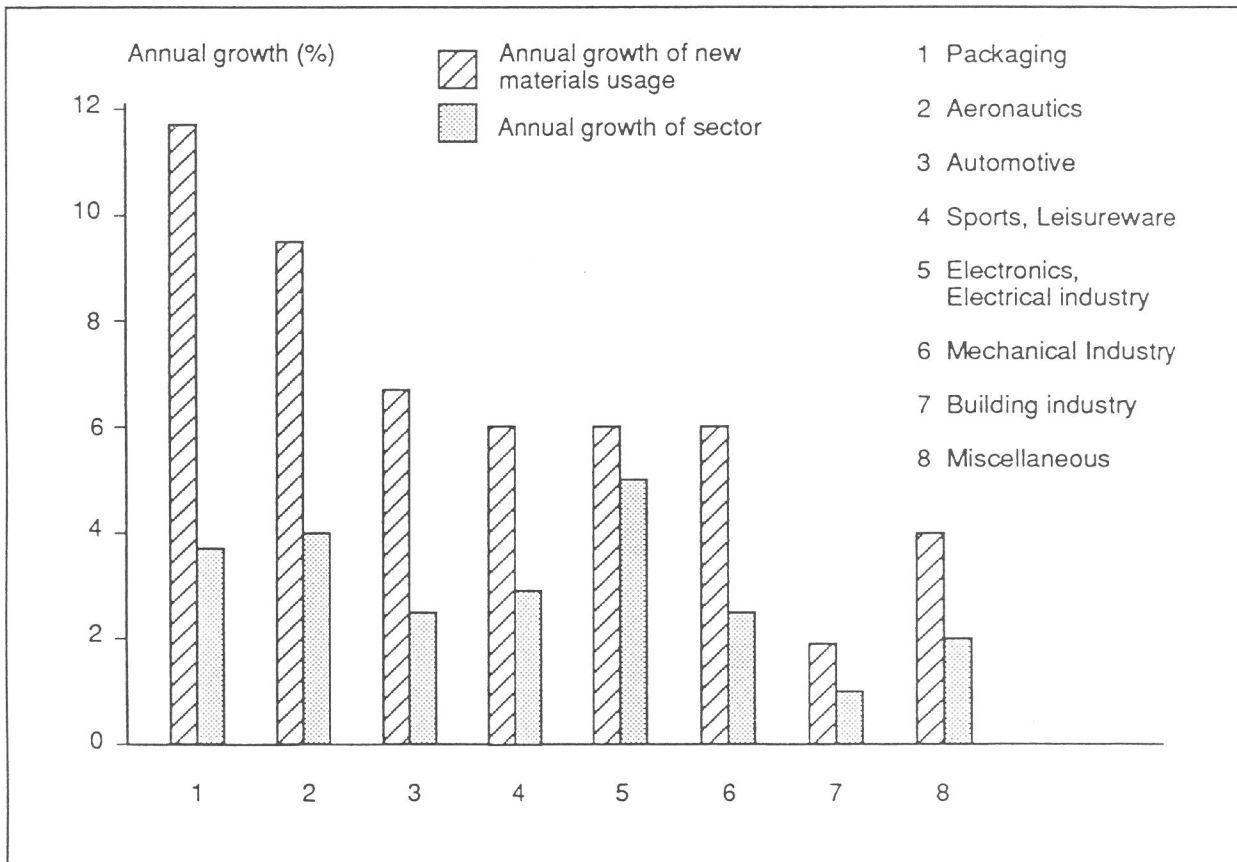


Figure 1.5 New materials usage forecasts by end user sector in Europe (1988)

## 2. Review of materials science and engineering

Because of the key enabling role of materials for all industrial technologies, the various areas of materials science and engineering will be reviewed in some detail.

### 2.1 Materials research

The trends and opportunities in materials research have been recently studied in depth by the Materials Research Advisory Committee of the US National Science Foundation (Ref. 2.1). Several overall trends in the field are noted, including:

- (i) Expansion of the frontiers of extreme physical condition (temperature, pressure, materials purity, etc.) leading to the discovery of new phenomena.
- (ii) The increasing sophistication and power of theory to confront the complexity of real materials. This is aided by computers and versatile numerical techniques on one hand and effective abstract concepts from statistical mechanics on the other hand.
- (iii) The careful study of model systems which isolate for study certain fundamental or technologically important systems. Examples range from clean surfaces of semiconducting and metallic single crystals to simple disordered, amorphous or glassy solid and to exotic liquid crystals in bulk and in films.
- (iv) A shift toward the study of complex materials and systems. Surfaces, interfaces, small particles, thin films and submicron structures (e.g. "nanocrystalline metals"), complex composite materials, systems with intricate microstructures, highly anisotropic solids and quasi one- and two- dimensional materials are important examples.
- (v) Increased sophistication in the methods of materials preparation. This involves advanced chemical synthesis and metallurgical processing as well as more recently developed fabrication techniques, such as rapid solidification, UHV vapour deposition, molecular beam epitaxy, and plasma induced oxidation.
- (vi) Fuller characterization of materials on the atomic scale which ultimately determines the macroscopic properties of primary interest. This is made possible by the development of a vast array of diagnostic tools which probe physical and chemical properties on an atomic scale.
- (vii) An increasing focus on understanding and controlling the processes used to make materials. The coupling of characterization methods to the fabrication process permits increasingly a proper control of the resultant product, and the tailoring of materials properties to specific physical requirements, for practical applications or for fundamental studies.

## 2.2 Materials processing

Advances in materials are often depending on (or are coupled with) progress in processing techniques. Some of the major newer processing techniques currently emerging are (Ref. 2.2):

### a) Solidification

Directional solidification has successfully been developed to produce anisotropic structures with improved properties. The first development was columnar grain structures which gave improved creep resistance because of the absence of transverse grain boundaries, which has led to producing single crystal turbine blades for use in aircraft jet engines. Rapid solidification processing produces non-crystalline (glassy or amorphous) alloys by cooling them very rapidly (about  $10^6$  deg/s) from the liquid or gaseous phase such that the atoms are frozen in their liquid configuration. Ribbons obtained by "melt-spinning" are typically 30 to 40  $\mu\text{m}$  thick and 3 to 5 mm wide, and can be 100 percent glassy with a very even section and smooth surface.

### b) Mechanical alloying

This process involves dry-milling suitable mixtures of metal and oxide powders in high-energy attrition mills to produce "composite" superalloy powders, an even dispersion of oxide in an already alloyed metallic matrix. This powder preparation may then be directly hot extruded and rolled to bar form, followed by heat treatment, to produce the required structure and properties of the oxide dispersion strengthened superalloy (ODS).

### c) Casting

Continuous casting whereby solidified metal is continuously drawn from an open-ended mould continually fed with liquid metal is now a commercially viable process for aluminium, copper, and steel in slab and bar form. Rheocasting is a technique for shaping metal in the semi-solid state. It involves rigorous agitation of the melt during the early stages of solidification, which breaks up the solidifying dendrite structure to form a viscous slurry that can be "cast" as an ingot.

### d) Powder metallurgy (PM)

By this technique, the material is first produced in powder form and then consolidated by pressing and high-temperature sintering. Powder forging involves hot forging in closed dies, the pre-forms made by PM techniques. The powder forged parts are more homogeneous in structure, have more isotropic mechanical properties, and have better dimensional accuracy and surface finish. Hot Isostatic Pressing (HIP'ing) involves simultaneous isostatic pressing (pressure-tight container in a pressure vessel) and sintering. HIP'ing can achieve more than 99 percent theoretical density in most metals and ceramics.

### e) Forming

Certain metals (e.g. Zn-Al, Cu-alloys, some stainless steels and light alloys based on Al and Ti) show superplasticity, i.e. uniform elongation under slow rates of strain at a temperature around  $0.5 T_m$ ; they can be moulded in a manner similar to thermoplastics. Explosive forming, on the other hand, involves using high- or low- energy explosives to press metals

against blocks or into die activities. By electroforming it is now possible to use standard electroplating tanks and techniques to form the whole component.

#### f) Surface technologies

A number of surface technologies has been brought to industrial applications in recent years, including Chemical Vapour Deposition (CVD) and Physical Vapour Deposition (PVD). Ion implantation which has been successfully used to dope semiconductors has been introduced to the metals industries to allow ion implantation into the surface of metal components to give special alloys with unusual properties. Laser surface treatments are now commercially possible, involving surface melting and surface alloying that provide new opportunities for modifying surface structure (surface homogenization, alloying or cladding) in a controlled manner.

## 2.3 Structural materials

Engineering materials for applications in which the mechanical (or mechanical-thermal) properties are critical for design are called "structural materials". They comprise traditionally mainly the broad classes of metals and alloys, ceramics, polymers and composites made of them. Some of the physical and mechanical properties that lead a designer to choose one material over another are shown in Figure 2.1 (Ref. 2.3). Many other properties are also important to a designer including corrosion and wear resistance, durability, reliability and, always, cost. From the overview data of Figure 2.1 the vast spectrum of structural materials with broadly varying properties is obvious. There is an intense continuous ongoing effort to improve structural materials in various directions; only some main trends (Ref. 2.4) can be discussed within the scope of this study.

### 2.3.1 Metals and alloys

Advances in basic metals (Ref. 2.5) are mainly possible through improvements in:

- (i) Purity and chemical control
- (ii) Microstructure specifications
- (iii) Processing and manufacturing techniques.

Advances in steel refining have led to remarkable improvements in composition control and cleanliness. Reduction in oxide and especially sulfide contents have resulted in significant improvements in ductility. A corresponding prospect of comparable importance is the potential removal of phosphorus. Phosphorus increases the sensitivity of high-strength steels to embrittlement phenomena, and its elimination would constitute a major advance in ferrous metallurgy.

An example of solid-state processing that has reached commercial scale in steel making is the controlled rolling of steels that are microalloyed with relatively stable carbide- and nitride-forming elements such as niobium, vanadium and titanium. In this process, particle precipitation is induced by plastic deformation at a controlled temperature during rolling, and a fine grain structure is obtained through a controlled schedule of temperature reduction and rolling. The results are the high-strength low-alloy (HSLA) steels that have been developed over the past few decades. A measure of the techno-economic success of these steels is their increasing



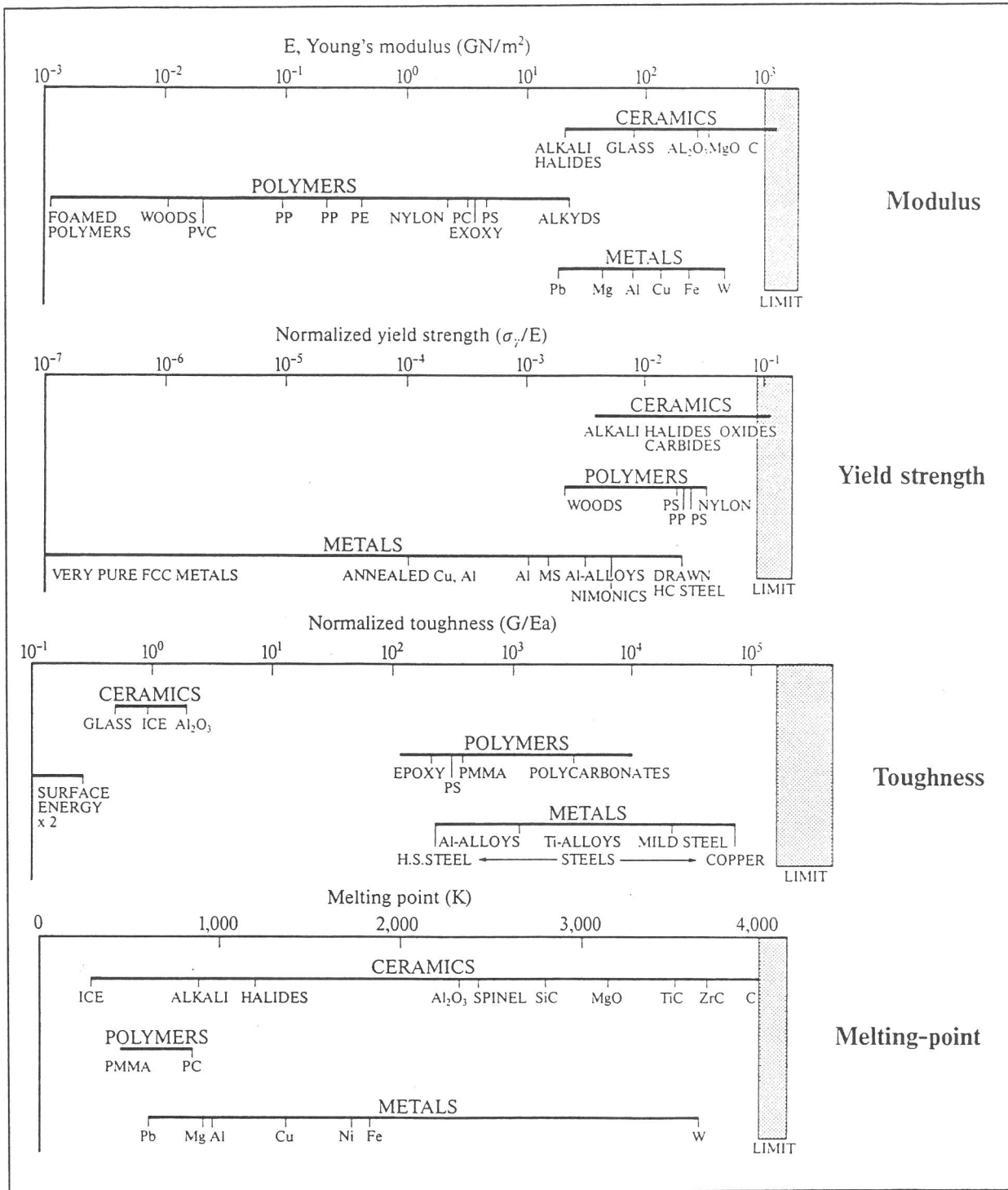


Figure 2.1 Properties of engineering materials

utilization in automobiles. According to Figure 2.2, the amount of HSLA steel used per vehicle has been increasing even more rapidly in recent years than the lower-density aluminium alloys, plastics and composites.

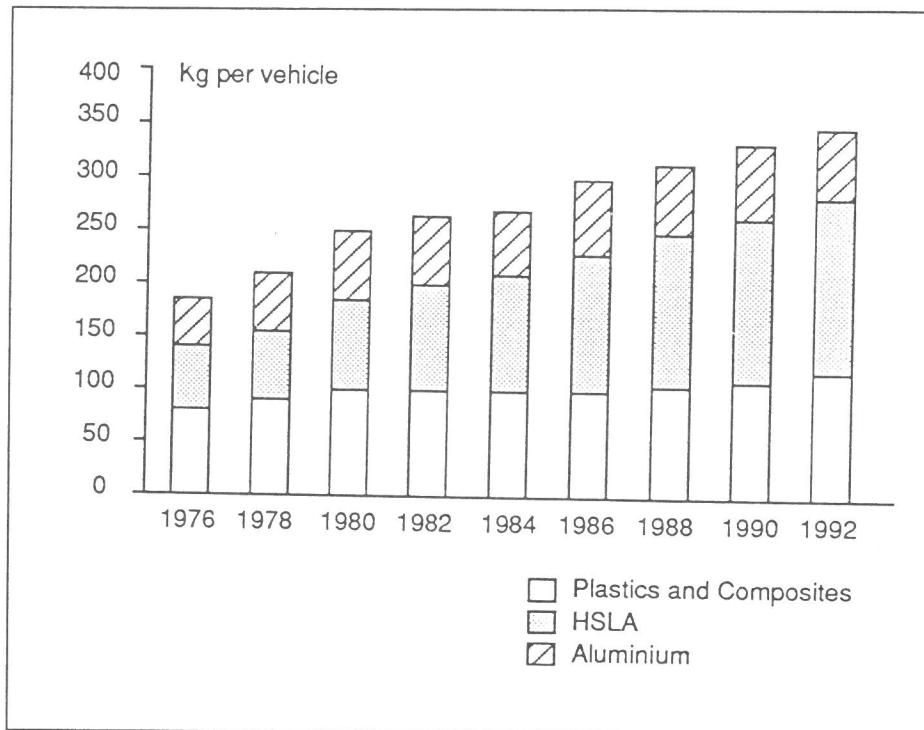


Figure 2.2 Materials use in US automobiles - status and trends

An important development in the HSLA steels are the "dual phase" steels (Ref. 2.6). By creating a ferritic-martensitic structure with 10 to 20 percent hard martensite it is possible to give such a material improved ductility and greater strength than other steels. This structure can be obtained in two ways: (a) by annealing in the austenite-ferrite range followed by rapid quenching (in the case of low alloyed MnV, MnTi or MnNb steels); or (b) by precise rolling and cooling (for the higher alloys of the CrMo or MnSiCo type).

For light weight, high-strength structures there is considerable interest in research on aluminium-lithium alloys (Ref. 2.6). An aluminium alloy of 2.5 percent lithium has a weight saving of 9 percent and a specific stiffness that is 20 percent higher than that of older aluminium alloys. The strength of this kind of material is obtained by coherent  $Al_3Li$  precipitates with dimensions of 10 to 100 nm. One disadvantage of aluminium-lithium alloys is their low elongation at break. This is improved by the addition of 1.3 to 2.1 percent copper. Grain growth and recrystallization are countered by adding 0.12 percent zirconium, which also improves stability at high temperatures.

With specific processing techniques, materials with unusual microstructures have been developed in recent years. Two classes of materials which are of great interest for future applications not only from a structural but also from a "functional" point of view are glassy metals and nanocrystalline metals:

- Some metallic alloys can display a non-crystalline (glassy or amorphous) state if produced by rapid solidification techniques. Examples are metal-metalloid alloys, like Pd80 Si20, Fe80 B20 and metal-metal alloys, like Ni60 Nb40, Cu50 Zr50. Metallic glasses are all very strong and stiff, the strongest known, Fe80 B20, is stronger than the best carbon fibre and almost as stiff. In addition, the corrosion resistance of metallic glasses is very promising and their electric resistivities are 3 to 4 times higher than conventional Fe or Fe-Ni alloys, and are almost independent of temperature over wide ranges.
- Nanocrystalline metals in which the grain size is of the order of nanometres have been made feasible by evaporation and fineparticle condensation techniques (Ref. 2.7). When the compacted specimen grain size is about 5 nm, the crystalline and interfacial phases have nearly the same volume fraction, assuming a grain boundary thickness of 1 to 2 nm, see Figure 2.3. This wholly new type of material can have very different properties from any material previously produced.

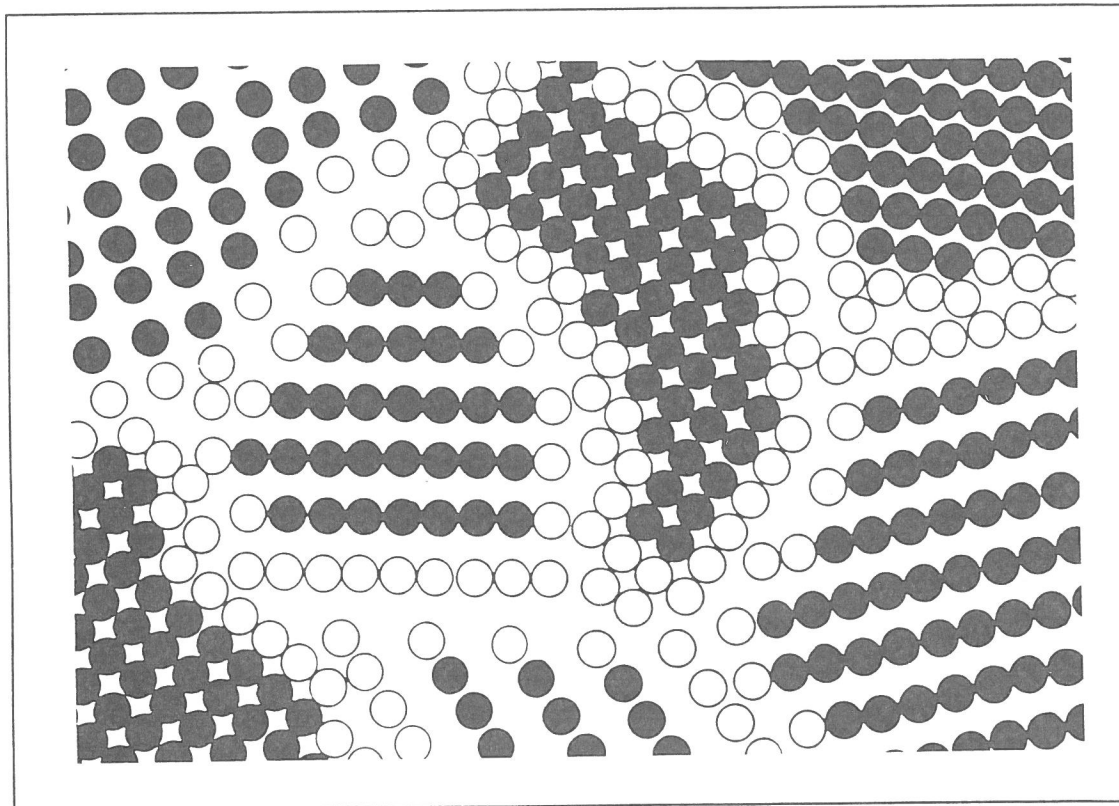


Figure 2.3 Structure model of nanocrystalline materials (black circles: atoms allocated to crystalline regions; open circles: atoms allocated to grain boundary regions)

### 2.3.2 Ceramics

The newer special engineering ceramics of current interest are alumina ( $\text{Al}_2\text{O}_3$ ), silicon carbide ( $\text{SiC}$ ), silicon nitride ( $\text{Si}_3\text{N}_4$ ), zirconia ( $\text{ZrO}_2$ ) and the Sialons (silicon aluminium oxynitrides). Their main valuable properties include high hardness, high stiffness, relatively low

density and high potential wear and corrosion resistance. A serious limitation of ceramics for structural applications has been their inherent brittleness and their susceptibility to thermal shock, i.e. they fracture when suddenly cooled. These drawbacks may be improved by reducing the size of "flaws", i.e. the small cracks introduced during raw material handling and manufacturing and by introducing toughening mechanisms through synthetic "crack-retarding entities" which should arrest or close cracks. Thus, the two main routes to improve structural ceramics are (i) refinement of processing and (ii) introduction of toughening mechanisms.

Of the multitude of processing techniques, the following three powder synthesis methods are particularly important:

- The preparation of monodisperse oxide powders, starting from alkoxides, using controlled hydrolysis. This method, which is suitable also for the deposition of thin layers of oxide materials, is relatively costly because of the investment in equipment. It is widely used for powder preparation on a laboratory scale when extremely high purity is required.
- The sol-gel process starts with an aqueous dispersion of ceramic particles. The dispersion is gelled by the extraction of water, after which the powder is obtained by drying the gel. The particles are generally small (5 to 50  $\mu\text{m}$ ) and spherical. Despite their relatively high production costs, sol-gel powders are used for a number of important applications.
- The preparation of powders after a gas phase process using a laser or in a plasma. Here, for example, silicon nitride is made from the gases silicon tetrachloride and ammonia or from silicon tetrachloride, nitrogen and hydrogen, the reaction product being formed by laser or plasma excitation. The great advantage of this (complex) technique is that very fine powders can be made with particle sizes down to 10 nm.

The current approaches to increase the toughness of engineering ceramics include reducing the size and concentration of pre-existing crack initiators (such as microcracks and pores) by decreasing grain sizes to the micron range and increasing densities to 99 percent or so. In addition, the following main mechanisms for crack retardation are applied (Ref. 2.4):

- Transformation-toughened ceramics (like partially stabilized zirconia, PSZ) contain dispersed small particles of a metastable phase (e.g.  $\text{Y}_2\text{O}_3$ , MgO in the case of PSZ) that transform crystallographically when the strain field of crack passes through or near them. In this way some of the energy of the crack is absorbed. If the transforming particles also increase in volume, they can apply a compressive stress to the crack tip, reducing its effective driving force.
- A second way to stop a crack is by spreading the stresses concentrated at its tip over a larger surface. This can be accomplished if minute cracks (called microcracks) are purposely created in the ceramic material during processing.
- Thirdly, ceramics can also be made crackresistant by interlacing with fine fibres or whiskers, as is the case in composite materials.

The operational life of structural industrial ceramic components must be predicted by a probabilistic approach, i.e. a combination of data obtained from Weibull statistics and fracture mechanics calculations. If reliability data (operating life at maximum loading) are necessary for a structure composed of a number of components, Weibull curves must be coupled to stress distribution studies.

One of the oldest industrial applications of ceramics is in cutting tools. The conventional solution has been to use steel or carbide tools with a wear-resistant surface of, say, titanium nitride, titanium carbide, aluminium oxide or a combination of two or more of these. Still greater grindig performance can be obtained through use of much more expensive materials - the synthetically produced cubic boron nitride and manmade diamond.

High-temperature applications of technical ceramics, in which properties such as good thermal shock resistance and the relatively excellent resistance to corrosion of some materials are important, have been at the forefront of attention for many years. Ceramics in internal combustion engines, gas turbines and high-temperature heat exchangers hold the greatest imaginative appeal. A number of technological and cost problems, however, are yet to be solved before the full potential of advanced ceramics can be realized in the market place. A list of new products made of advanced structural ceramics already being used in automobiles is given in Table 2.1 (Ref. 1.4).

Table 2.1 Structural ceramics currently used in automobiles (examples)

Component	Material
Mechanical seal for water pump	Al <sub>2</sub> O <sub>3</sub>
Catalyst pelleted support	Al <sub>2</sub> O <sub>3</sub>
Catalyst monolithic support	MgO · Al <sub>2</sub> O <sub>3</sub> · SiO <sub>2</sub>
Fibre for FRM piston	Al <sub>2</sub> O <sub>3</sub> · SiO <sub>2</sub>
Heat insulator for catalyst	Al <sub>2</sub> O <sub>3</sub> · SiO <sub>2</sub>
Glow plug for diesel engine	Si <sub>3</sub> N <sub>4</sub>
Precombustion chamber for diesel	Si <sub>3</sub> N <sub>4</sub>
Rocker arm tip	Si <sub>3</sub> N <sub>4</sub>
Turbochargers	SiC, Si <sub>3</sub> N <sub>4</sub>

### 2.3.3 Polymers

The major polymers can be broadly divided into

- (i) Thermoplastics, whose polymer chains are not chemically bonded to each other and can be melted or softened by the application of heat,
- ii) Thermosets, whose polymer chains are bonded chemically, producing a three-dimensional network that cannot be melted by heating,
- (iii) Elastomers or rubbers, which can deform elastically by several hundred percent.

Polymeric materials are increasingly being used as replacements for metals in existing industries and for completely new products in emerging industries. Their attractiveness is largely the ease with which they can be formed to complex shapes at only modestly high temperatures by injection moulding. For general engineering use polymers have two major deficiencies: lack of stiffness and poor elevated temperature properties when compared with metals; the maximum operating temperatures for the best heat-resisting thermoplastics are about 300 °C. However, in recent years new grades of polymers with a new price/performance ratio which have the ability to "tailor-made" materials have been developed by combining materials: polymer with polymer, polymer with elastomer, polymer with inert fillers and reinforcements.

The tensile strength and elastic modulus of crystalline and glassy polymers is comparable with wood, see Figure 2.1. The specific strength (i.e. strength/density) is comparable with steel. Both the tensile strength and the elastic modulus may be increased by drawing crystalline polymers into fibres, whereupon their mechanical properties become comparable to aluminium alloys. The drawing process unfolds the molecular chains which become aligned in the drawing direction; and the fibre reflects the superior properties along the axis of the molecular chains. Examples of high strength fibres are:

- Polyethylene fibres may be drawn to give an elastic modulus of about 150 to 250 GPa and a strength of about 3.5 to 7.0 GPa; however, they still melt below 150 °C.
- Carbon fibre, produced by heating and carbonizing drawn polyacrylonitrile, has an elastic modulus of about 200 GPa and a strength of about 1.5 GPa. Treatment in argon at 1700 °C increases the strength to about 3 GPa, and annealing at 2600 °C can put the modulus upon to 400 to 600 GPa.
- Kevlar fibre (diameter ca. 7 µm) is a polyaramid in which the molecules consist of amide and carbonyl groups separated by rigid phenylene rings. The fibres have an elastic modulus of about 30 GPa (which may be increased to 70 GPa by annealing at 400 °C) and "as-spun" strengths of about 2.5 GPa up to several hundred degrees Celsius.

The main advantage of thermoplastics for engineering applications are: ease of shaping (pressing, injection moulding, extrusion, thermoforming, etc.), low density (about 1g/cm<sup>3</sup>), toughness comparable with metals, see Figure 2.1, orientability (fibres, biaxially strengthened films, tapes, etc.). In addition, the good chemical resistance of, e.g. polyethylene, polyvinylchloride and polypropylene make them useful for domestic piping, drainage, rainwater goods, etc.

Filled thermosets, like polyester and vinyl esters which are established polymers of recognized stability in the marine and chemical industries, are now finding a variety of uses, both structural and decorative, in building. In addition, plastic foams (from thermosets or thermoplastics) are finding increasing applications for structural purposes. These fine-celled foams are sufficiently rigid and strong to bear modest loads (e.g. panels, furniture) or even tough and flexible for shock absorption.

Polymer blending, which was first applied in order to increase the toughness of brittle amorphous polymers, such as polystyrene, polyvinylchloride and polymethylmethacrylate, is now routine. In a glassy polymer combined with a relatively small proportion of an elastomer, the rubber particles toughen the material by enabling it to absorb energy more efficiently as it is

fractured. Recently, a new class of immiscible blends has been developed - the so-called "high performance" blends - incorporating several components (e.g. polycarbonate with polybutylene terephthalate) that are more or less equal. Because neither polymer is the dominant component, the two phases exist in an intricate interpenetrating network. The blend's resistance to heat and solvents is higher than pure polycarbonate, and its durability makes it a candidate for the replacement of metal in automotive components such as bumpers.

At present, an appreciable proportion of all polymers produced becomes waste within a few months. In view of the consequences of this for the environment there is now a considerable pressure and incentive to find ways of recycling such materials.

### 2.3.4 Composites

Composites are intimate mixtures of two or more materials aiming that the resulting properties of the composite are superior to those of its individual constituents. For structural purposes the objective is to increase strength and rigidity, perhaps simultaneously reducing density. The vast majority of composites are those in which fibres serve as reinforcement, such as glass fibres, carbon fibres, boron fibres, alumina fibres. Promising (but very costly) new fibre materials are rapidly solidified fibres with amorphous or microcrystalline structures and metal or ceramic single crystal whiskers grown specifically to contain very low dislocation densities and thus very high yield strengths.

The main composite systems are (Ref. 2.2):

- Fibre-reinforced plastics, initially based on the thermoset plastic moulding materials, polyester, epoxy, phenolic or silicone resins, with various reinforcements, mainly glass, carbon or Kevlar fibres. They provide strong, low density and easily fabricated materials for structural purposes and a maximum working temperature of about 180 °C. Thermoplastics (injection-moulded) are also being used as matrix materials. In load-bearing applications a polyamide matrix gives the best overall mechanical performance in terms of strength and modulus over a fairly wide temperature range. Compounds based on polyethersulfone (PES) and polyetheretherketone (PEEK) are suited for applications where higher temperature performance is required. Carbon-fibre reinforced plastics are beginning to appear in engineering in applications where weight saving is at a premium.
- Fibre-reinforced metals assumed to improve the high-temperature performance of nickel and titanium matrices by incorporation of tungsten and carbon or boron fibres were not successful because of problems such as inter-diffusion and oxidation damage. Much of the development work on metal matrix composites is now concentrated on low-temperature systems, mainly based on carbon or boron fibres in aluminium. Merits of these systems are good tensile strength, elastic modulus and compressive strength both parallel and normal to the fibres, relatively high impact strength and fracture toughness, high specific strength, high softening temperatures and ease of joining by welding, brazing or diffusion bonding.
- Fibre-reinforced ceramics are suited in principle for temperatures above those at which a metal matrix can serve. Ceramic materials for the matrices cover a wide range, including silicon carbide, silicon nitride, aluminium oxide or mullite and zirconia. Fibres of the same or other materials are embedded within the matrix to produce the composite. Many believe that composites are the best route to wide applications of ceramics as structural materials. Carbon-carbon composites retain much of its strength up to 2500 °C, they are used in the nose cone of re-entry space vehicles. Unlike most ceramic-matrix composites, they are

vulnerable to oxidation at high temperatures, so a thin layer of ceramic is often applied to the surface to protect it.

- Fibre-reinforced cements with matrices of the stronger low-porosity macro-defect-free (MDF) cement (see Section 2.5.1), reinforced with fibres derived from glass, polypropylene, cellulose, amorphous metal ribbon, and stainless steels are receiving a lot of attention. They are of interest both from a structural engineering point of view and for health and safety reasons, as replacement for the asbestos filled cement traditionally used in building for roofing, gutters, pipes, etc.

## 2.4 Functional materials

The term "functional materials" denotes classes of materials which are used in various branches of industry because of their specific functional purposes - for example, electric, magnetic or optical functions. They play an enabling role in some of the key techno-economic areas such as the electronic industry or in contemporary information technology (Ref. 2.8). The field of functional materials is extremely broad; only a few general trends can be discussed within the scope of this study.

### 2.4.1 Electronic materials

The increasing complexity of electronic systems is forcing semiconductor technology to very large scale integrated (VLSI) circuits. This requirement for microminiaturization will require the development of new techniques for etching ever finer features onto a chip; some promising approaches include the use of electron beams and X-rays rather than visible light to define the circuit pattern. Newer chip designs and newer chip materials are moving beyond the limits of silicon leading to the proposal of three-dimensional chips (in which circuit components are arranged in stacked rather than single layers on a chip's surface) and to the application of gallium arsenide. Transistors made from gallium arsenide could have two to five times the switching speed of silicon transistors leading to faster and more powerful computers.

A key to the continued progress in VLSI technology is the refinement and development of new materials characterization tools. Structural defects such as dislocations and stacking faults play an important role in determining the electronic properties of semiconductors. Thus, continued development of high resolution electron microscopy techniques is important, in conjunction with the development of other methods for "imaging" the properties of materials.

Plasma assisted deposition of conductors, insulators and barrier layers is common practice in semiconductor manufacturing. Molecular beam epitaxy (MBE) offers precise control of layer thickness and will be important for high speed devices, as well as for semiconductor lasers and integrated circuits. Advances in the complexity of integrated circuits place demands not only on the semiconductor materials themselves but on a variety of materials associated with the chip and its "package".

An important class of materials for electronic applications are nowadays ceramics. The chemical compositions, crystal structures and the function and application of many new electronic ceramics are summarized in Table 2.2 and Table 2.3 (Ref. 1.8).



Table 2.2 Ceramics for electronics applications (examples)

Crystal structure	Chemical composition	Function and application
Perovskite type ( $ABO_3$ )	$BaTiO_3$ , $SrTiO_3$ , $CaTiO_3$	capacitor
	$Ba[Zn_{1/3}(Nb,Ta)_{2/3}]O_3$ , $(Sr, Ca)[(Li_{1/4}Nb_{3/4}), Ti]/O_3$	microwave dielectrics
	$Pb(Ti, Zr)O_3$ , $Pb[Mg_{1/3}Nb_{2/3}], Ti, Zr]O_3$	piezoelectrics
	$PbTiO_3$	pyroelectrics
	$(Pb, La)(Ti, Zr)O_3$	electrooptics
	$(La, Sr)CoO_3$	heater
	$Ba(Pb, Bi)O_3$	superconductor
Spinel type ( $AB_2O_4$ )	$(Mn, Zn)Fe_2O_4$	soft ferrite, magnetic head
	$CoFe_2O_4$	memory ferrite
	$(Mn, Cu)(Mn, Co, Ni)_2O_4$	thermistor
	$Mg[Al, Cr, Fe]_2O_4$ , $CoAl_2O_4$ , $NiAl_2O_4$	high-temperature thermistor

Table 2.3 Ceramic sensors (examples)

Sensor	Sensor ceramic material	Sensor function
Temperature	$(Mn, Cu)(Mn, Co, Ni)_2O_4$ , $CoAl_2O_4$ , $NiAl_2O_4$ , $Mg(Al, Cr, Fe)_2O_4$ , $SiC$	NTC thermistor
	$BaTiO_3$ , $VO_2$ , $(Mn, Zn)Fe_2O_4$	PTC thermistor temperature switch
Humidity	$MgCr_2O_4-TiO_2$ , $V_2O_5-TiO_2$ , $ZnCr_2O_4-LiZnVO_4$ , $Al_2O_3$ , $Ca_{10}(PO_4)_6(OH)_2$	$H_2O$ (ionic conduction)
	$ZrO_2-MgO$	$H_2O$ (electronic conduction)
Gas	$SnO_2$ , $ZnO$ , $\gamma-Fe_2O_3$ , $\alpha-Fe_2O_3$ , $TiO_2$ , $CoO-MgO$	$CH_4$ , $i-C_4H_{10}$ etc. (electronic conduction)
	$ZrO_2-CaO$ , $MgO$ , $Y_2O_3$	$O_2$ (ionic conduction)
Ion	$AgX(X: Cl, Br, I, CN, SCN)$ $PbS-Ag_2S$ , $CdS-Ag_2S$ $CuS-Ag_2S$ , $LaF_3$	ion-selective electrode
Position- velocity	$Pb(Zr, Ti)O_3$	piezoelectricity
Optics	$PbTiO_3$ , $LiTaO_3$	pyroelectricity
	$LiNbO_3$ , $Pb(Zr, Ti)O_3$ , $CaF_2$ , $Li_2B_4O_7$	(infrared detection) thermoluminescence

## 2.4.2 Magnetic materials

"Soft" magnetic materials (originally, simply iron) are used most widely in transformer applications where low energy loss is desired. Special grain-oriented silicon steels have been developed over the past 50 years to provide lower losses than ordinary irons or steels. However, new metallic glasses made by the rapid-solidification process exhibit only one twentieth to one third the core loss of the best steels available.

There have also been recent major advances in "hard" magnetic alloys - alloys that can be magnetized to a high value and retain that magnetism. Figure 2.4 shows how the "energy product" of permanent magnets has improved over the past decades (Ref. 2.8). These new materials have contributed to the design of advanced electric motors, generators, actuators and electro-acoustical devices, for example.

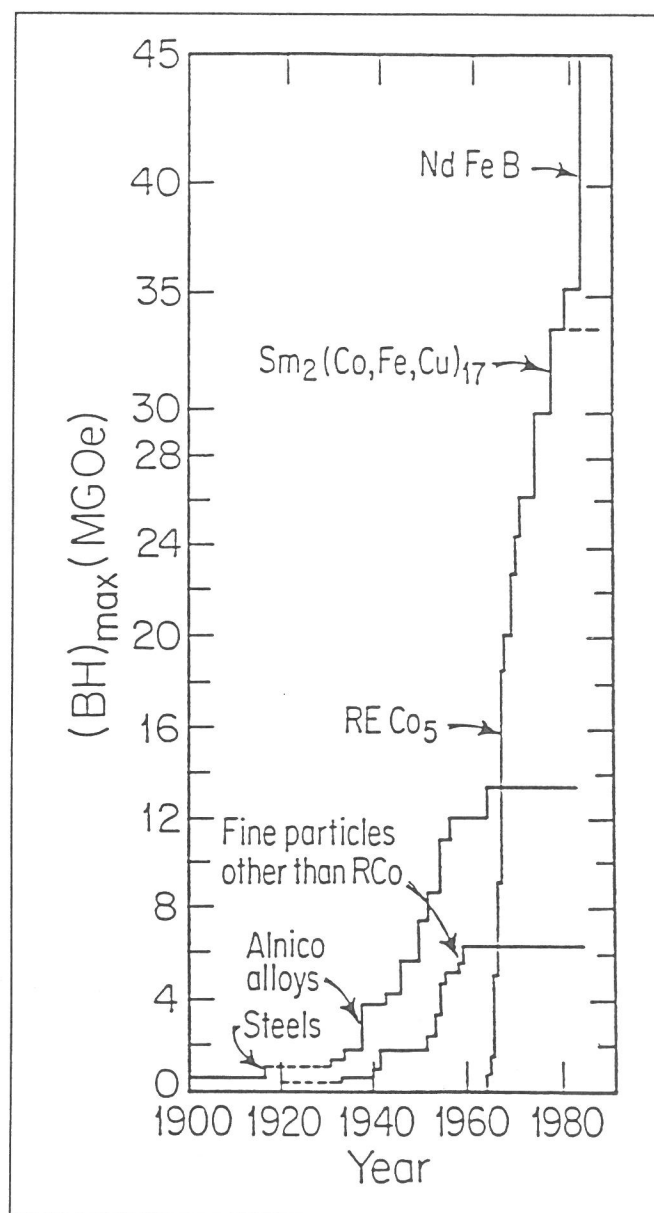


Figure 2.4 Development in hard magnetic materials since 1900

For magnetic storage media - which are essential for contemporary information technologies - two distinct materials types are in use today: particulate - in which the magnetic ingredient consists of submicroscopic, single-domain particles of oxide or metal immersed in a polymeric binder - and thin films of ferromagnetic metals and alloys.

### 2.4.3 Superconductivity

Of great current excitement are the high-temperature superconducting perovskites (for example Ba-La-Cu-O, Sr-La-Cu-O). These were first shown to be superconducting in 1986. Superconducting transition temperatures in excess of 90 K were confirmed early in 1987. Figure 2.5 shows the remarkable increase of achievable transition temperature in superconducting materials since their first discovery in 1911 (Ref. 2.8).

There is hope that even higher transition temperatures will be achieved and the expectation that current-carrying capacity will be great enough for practical devices and conductors, and that the pertinent materials can be fabricated in an applicable manner.

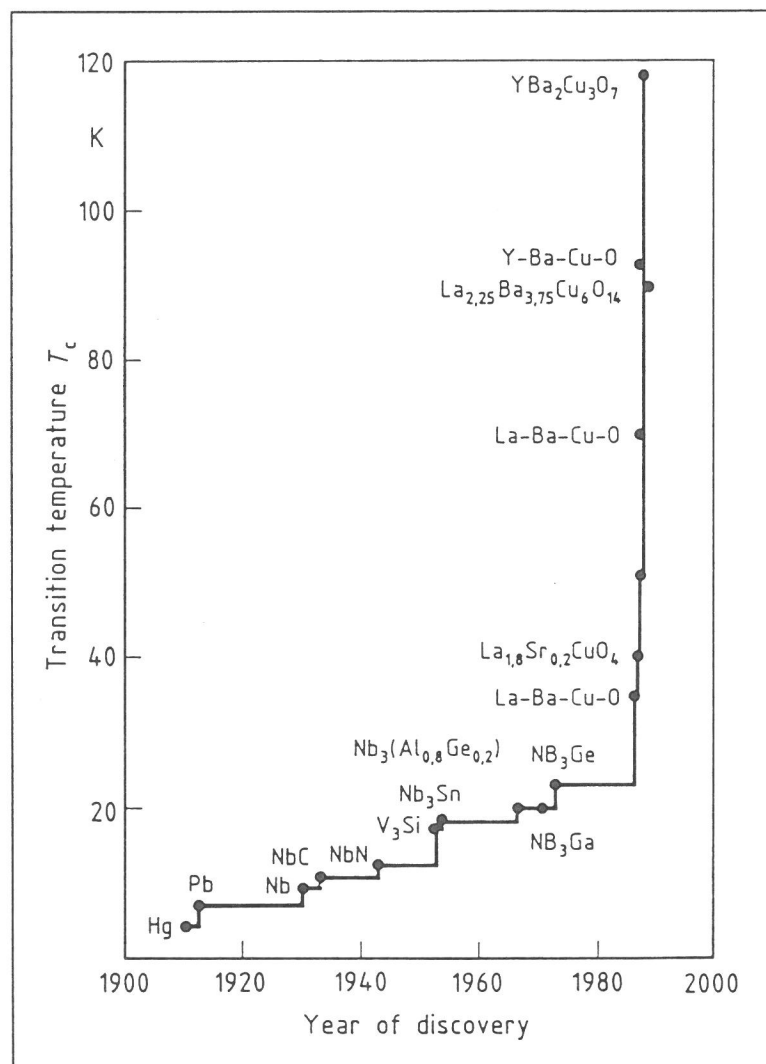


Figure 2.5 Transition temperatures in superconducting materials from 1911 to the present

#### 2.4.4 Photonics

There is increasing interest in expanding the possibilities of information technologies by photonics. In a photonic system, information is carried by pulses of light. The light source is a semiconductor laser or a light emitting diode, and the transmission medium is a hair - thin fibre guide or silica glass. Light pulses (and thus, information) can be transmitted through optical fibre at a rate much higher than the pulse rate of electrical signals sent through coaxial cable.

Photonics owes part of its remarkably rapid progress to advances in laser technology. The most effective lasers utilize compound semiconductors such as indium-gallium-arsenide phosphide. Also glass can now be made so pure and transparent that a light signal can travel for hundreds of kilometres before it has to be regenerated.

Glass is also displacing copper as material for telephone cables: optical-fibre guides now account for about a third of the growth of the "feeder routes" that carry telephone channels from central offices to clusters of users.

#### 2.4.5 Sensors

Another area of application of functional materials is in sensing devices. Examples of modern sensors are ceramics, which change their electrical properties when exposed to specific gases or other substances. The chemicals reversibly change the ceramics' electrical resistance, and sensing devices can be constructed based on that principle. The non-reactivity and corrosion resistance of ceramics allow sensors made from these materials to perform with considerable effectiveness in harsh chemical environments, for example, in measuring exhaust contaminants in internal combustion engines. In Table 2.3 (see page 21) examples of ceramic sensors are listed (Ref. 1.8).

### 2.5 Civil engineering materials

Despite their long history, civil engineering materials, such as cement, concrete and plaster, are the subject of continuous application-oriented research and development which is creating materials with new and improved properties to meet the demands for new buildings, housing, road and bridges for a growing world population (Ref. 2.9).

#### 2.5.1 Cement

Portland cement (annual world production: 800 million tons), the "glue" in the most widely used composite material concrete is a typical representation of "low-technology" ceramics. For acceptance as a more general engineering material, it has been attempted to increase the fracture strength by reducing the flaw size (according to Griffith's fracture criterion). Reducing porosity and pore size, the so called Macro Defect Free (MDF) cement with considerably improved mechanical properties has been developed (unnotched bend strength of 150 MPa, comparable with the strength of aluminium and polymers like PVC). It is possible that the new MDF cement may in some cases provide cheap substitute materials for metals and polymers, not only because of improved strength, but also low density ( $2.5 \text{ g/cm}^3$ ), stiffness (elastic modulus of 50 GPa), corrosion and heat resistance, low thermal conductivity, good acoustic damping, and ease of moulding (and colouring).

### 2.5.2 Concrete

Concrete (annual world production 7000 million tons or 3000 million m<sup>3</sup>) is an artificial stone made from cement, sand and various kinds of aggregate such as gravel. It has high compressive strength (10 to 100 MPa) but is brittle in tension (flexural strength 3 to 8 MPa) and cracks readily. Many possibilities exist for modifying the properties of concrete: for example, by using admixtures to control setting rate or to prevent bleeding and shrinkage; by using plasticizers to improve workability; by incorporating various polymers in the fresh concrete, and by reinforcing, using fibres of various materials, such as steel, glass, polyamide, polypropylene, Kevlar, or carbon or natural fibres. Polymer impregnated concrete can be made with strength well above those of conventional concrete (for example strengths of 15 to 25 MPa, elastic modulus of 40-50 GPa), but at a considerable premium in terms of direct materials cost and energy. The wide range of materials that can be used in modern concrete technology is shown in Table 2.4 (Ref. 2.9).

Table 2.4 Materials used in contemporary concrete technology

Binder systems	Aggregates	Reinforcing systems	Admixtures
Portland cements	Natural sands and gravels	Ordinary steel bars	Additives — for example, retarders, accelerators, stabilizers, air-entraining agents, workability aids, water-reducing agents
Blended cements	Crushed aggregates	Wire mesh, glass fibres, steel fibres, polymer fibres	Fly ash, silica
Special cements (with or without admixtures)	Natural light aggregates	Special-purpose steel bars and steel cables	Polymer dispersions, epoxy resins, emulsions
Cementitious materials, mostly reacting with water	Pyro-processed lightweight aggregates	Pre-stressing systems	
	Natural heavy aggregates	Glass fibre tendon systems	
	Inorganic and organic wastes		
	Special inorganic and organic products		

### 2.6 Renewable materials

The most economically important renewable resources and the recycling materials based on them are wood, waste paper and straw. In the industrialized countries, the consumption of based materials - plywood, fibreboard and particle board, and articles moulded from fibres or chips - is rising steadily. Figure 2.6 demonstrates this trend in Western Europe (Ref. 2.10).

The dwindling global supply of roundwood brought on by the devastation and over-utilization of forests and the effects of pollution will precipitate an increased use of smaller-diameter wood in the future. The greatest disadvantage of smaller woods, its high proportion of knots, may be compensated by new technologies.

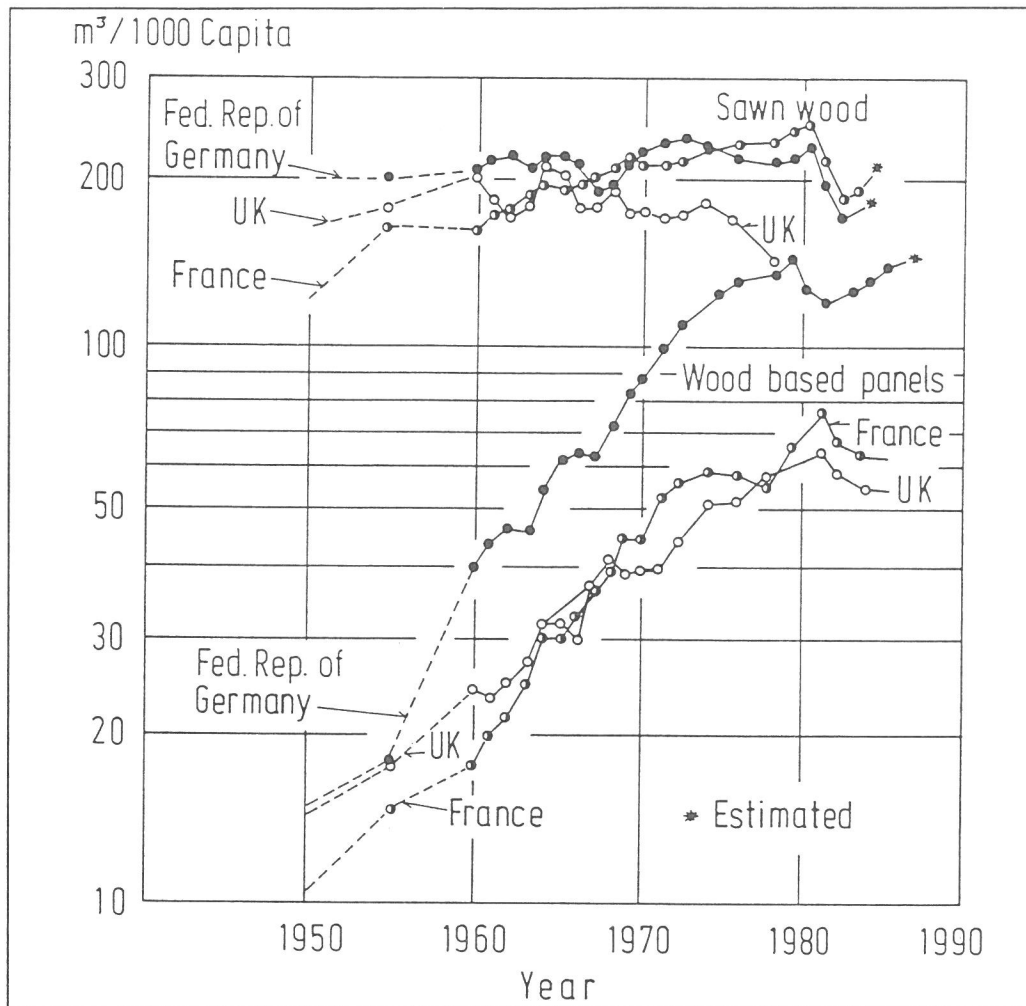


Figure 2.6 Consumption of sawn timber and wood-based panels in Western Europe

Solid wood panels may be glued with splines to form long elements (gluelam technology). Also new types of panels with improved properties are being developed. For example, the oriented structural board (OSB) technology uses special chips or strands, which are oriented by special equipment to produce a product whose strength is comparable to that of clean solid spruce of the same specific gravity. Based on technological developments and economic considerations, the following trends in utilizing renewable resources may be outlined:

- The substitution of solid wood by wood-based materials will increase.
- The panel industry will be able to utilize the growing amounts of smaller wood by applying specific technologies.
- The production capacities of plants utilizing small-diameter wood will increase.
- Wood-based materials will be improved by the use of a variety of special resins.

## 2.7 Biomedical materials

Materials of various kinds have been used to "repair" the human body when accidents, war, illness or congenital atrophies are incapacitated it from fulfilling a given function (Ref. 2.11). For example, prosthesis have become a significant economic sector with a worldwide market

of more than US\$ 2.3 billion in 1983 (\$ 1.3 billion in cardiovascular prosthesis and \$ 900 million on orthopaedics representing the two major areas). The output in medical and surgical equipment and orthopaedic appliances in the EC amounts to 5.5 billion ECU in 1988 (Ref. 1.1). In Table 2.5 an overview on major biomaterials and their primary uses is given (Ref. 2.2).

In examining prostheses three criteria arise:

- (i) aesthetic and social acceptability;
- (ii) biocompatibility, in the sense of a prostheses not harming the host organism (non-toxicity; lack of rejection);
- (iii) biofunctionality, or mechanical and corrosion resistance, which allows prostheses to fulfill their functions for extended periods without alteration.

**Table 2.5 Biomaterials and their major uses**

Material	Major uses
<b>Metals and alloys</b>	
316 stainless steel	orthopaedic fracture plates, joint replacement prostheses
Cobalt-chromium alloys	orthopaedic fracture plates, joint replacement prostheses, denture bases, heart valves
Titanium and its alloys	orthopaedic fracture plates, dental implants, cranial plates
Platinum metals	electrodes
<b>Plastics, elastomers, and fibres</b>	
Polymethylmethacrylate	dentures, cement for fixation of orthopaedic prostheses, ophthalmic implants and contact lenses
Polydimethylsiloxane	soft-tissue reconstruction (e. g. breast, facial contours), finger joint prostheses
Polyethylene	joint replacement prostheses
Polypropylene	finger joint prostheses, heart valves, sutures
Segmented polyurethane and natural rubber	blood-compatible materials for artificial hearts
Polyethylene terephthalate and fluorocarbon polymers	arterial prostheses, heart valve sewing rings, meshes for soft-tissue reconstruction
Hydrogels	blood-compatible surfaces, ophthalmic prostheses
Polylactic and glycolic acids	absorbable sutures and degradable prostheses
Cyanoacrylates	adhesives
<b>Ceramics and glasses (largely experimental)</b>	
Oxide ceramics (e. g. alumina)	joint replacement prostheses
Ion-leachable glasses	dental cement, coating for orthopaedic prostheses
Carbons	heart valves, dental implants, percutaneous implants

For biomedical materials and components in general, two essential elements of the subject should be noted. The first element concerns the rivalry between two apparently different modes of approach: on the one hand, the possibility of transplanting of tissue or a living organ, and on the other hand, the attempt to find a biocompatible, biofunctional material. The second element is the development of biomaterials. These materials are of several types: they may have the same structure as bone and would thus be prone to gradual colonization by bone cells; they may be biodegradable materials which encourage cell growth before disappearing completely; or they may simply be inert materials with exceptional properties not likely to cause side-effects.

### 3. The product cycle: A guide for the analysis of future requirements

The analyses of R&D needs in industrial and materials technologies to be described in the following Chapters must be oriented on the "total life cycle of products" (Ref. 1.4) in order to consider all relevant aspects. Industrial products and the materials used in the construction of machines, devices, habitation and other everyday necessities of man move in cycles: Raw materials such as ores, hydrocarbons and wood from the earth, or oxygen, nitrogen and other gases from the atmosphere are converted into simple metals, chemicals and other basic materials through refining and purifying processes. These basic materials in turn are modified into alloys, ceramics, polymers, composites or other engineering materials for design and manufacture into products; the products - after termination of their functional purpose and performance - are transformed into waste through the service use, deterioration and aging. By recycling or disposal, the waste materials are eventually returned to the earth, water or atmosphere but in quite different shape and composition.

As energy is needed in exploration, processing, production, service use or recycling all "materials cycles" are interconnected by "energy cycles". Energy production again utilizes the earth's resources - coal, oil, uranium, oxygen, and water, for example - so that the "total product cycle" also includes all substances for producing energy. It is obvious, that the character of the materials and energy cycles influence, and are influenced by, economics.

The task of engineers is to develop and select materials, improve the properties, and design constructions and processes, taking into account the most economic use of materials.

In Figure 3.1 the main aspects of industrial and materials technologies together with requirements in connection with engineering and general tasks are compiled with respect to the sequence of the product cycle - symbolized by key terms from top to bottom in the left part of Figure 3.1. Without going into details it can be seen that numerous aspects must be recognized in attempts to analyse future R&D needs in industrial and materials technologies.



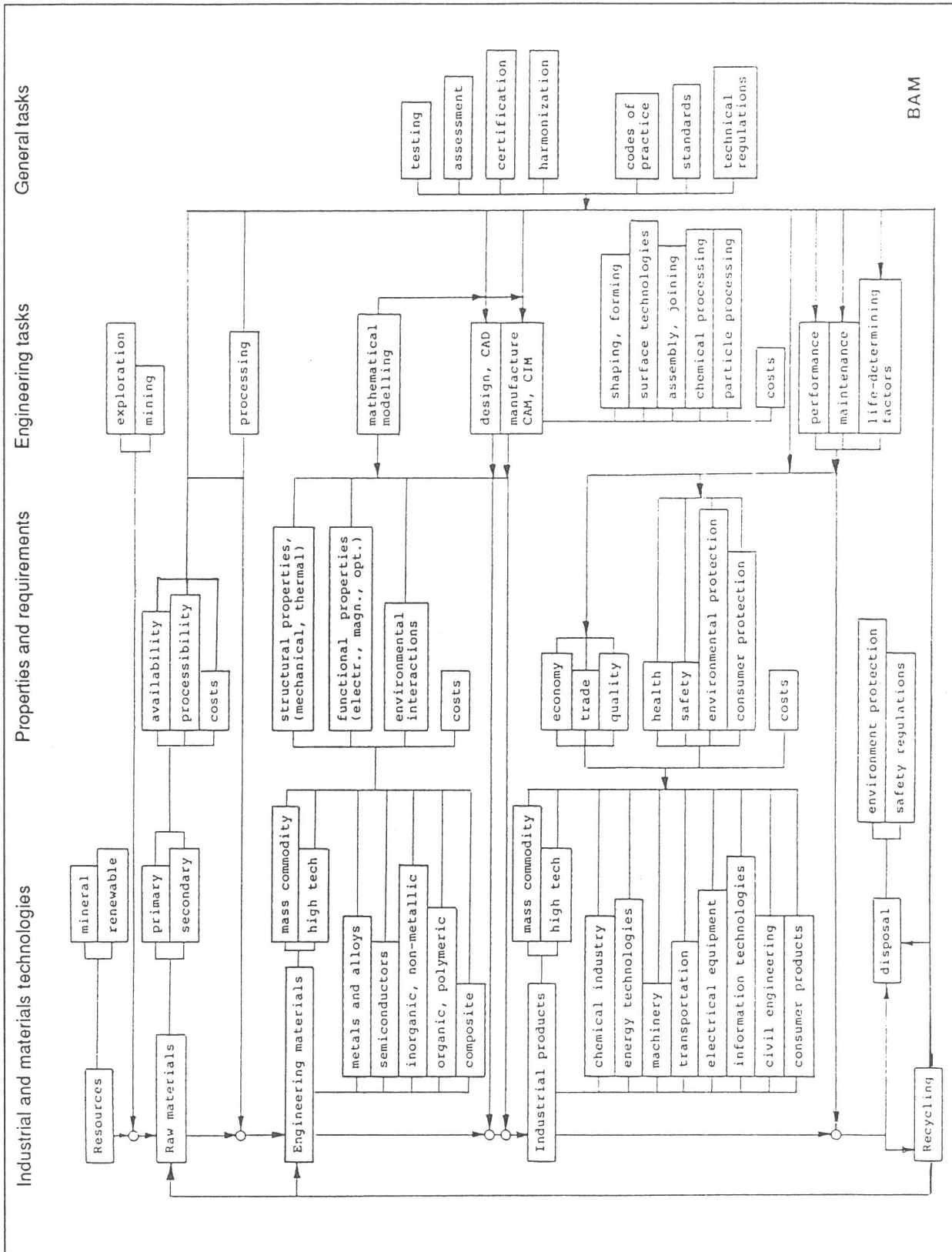


Figure 3.1 Characteristics of industrial and materials technologies and connected tasks

## 4. Research and development trends and needs: results of an enquiry

In order to determine on a broad basis R&D needs in industrial and materials technologies, an enquiry was made. Utilizing experiences in the performance of a previous enquiry to work out the first BRITE (Basic Research in Industrial Technologies for Europe) programme (Ref. 4.1), a questionnaire was developed and sent to about 700 institutions in all countries of the European Communities consisting of industries, universities and research organizations. The questionnaire contained the following questions:

- What are the prime important R&D requirements in the fields of:
  1. Materials and properties?
  2. Design?
  3. Manufacturing and processing?
  4. Performance needs?
  5. Testing and evaluation?
  6. Other (e.g. crucial operating conditions, environmental impact, recycling, quality assessment)?

A response of 140 filled-in questionnaires reflecting all main industrial, technological and scientific sectors was received with the following distribution:

- industry: 70 %
- universities: 24 %
- research organizations: 6 %.

For the evaluation of the answered questionnaires a data- bank computer programme was applied. From the answers in the questionnaire a total of 3010 entries was fed into the computer and the distribution of answers with respect to the following 8 basic groups was determined:

- I. Industries interested in R&D
- II. General tasks for R&D in industrial and materials technologies
- III. Products characteristics suggested for R&D
- IV. Materials suggested for R&D
- V. Materials properties suggested for R&D
- VI. Design techniques suggested for R&D
- VII. Manufacturing and processing technologies suggested for R&D
- VIII. Testing and assessment techniques suggested for R&D

## 4.1 Generals tasks for R&D in industrial technologies

Results of the computerized analyses of the questionnaires were obtained in the form of diagrams characterizing the distribution of answers in the named 8 areas. In addition, key words for R&D needs and suggestions were compiled. An overview on general R&D tasks is given in Figures 4.1 to 4.3.

Figure 4.1 indicates that a broad spectrum of industrial branches is interested in R&D in industrial and materials technologies, namely

- Chemical industries
- Electrical engineering
- Mechanical engineering
- Motor vehicles
- Aerospace
- Civil engineering.

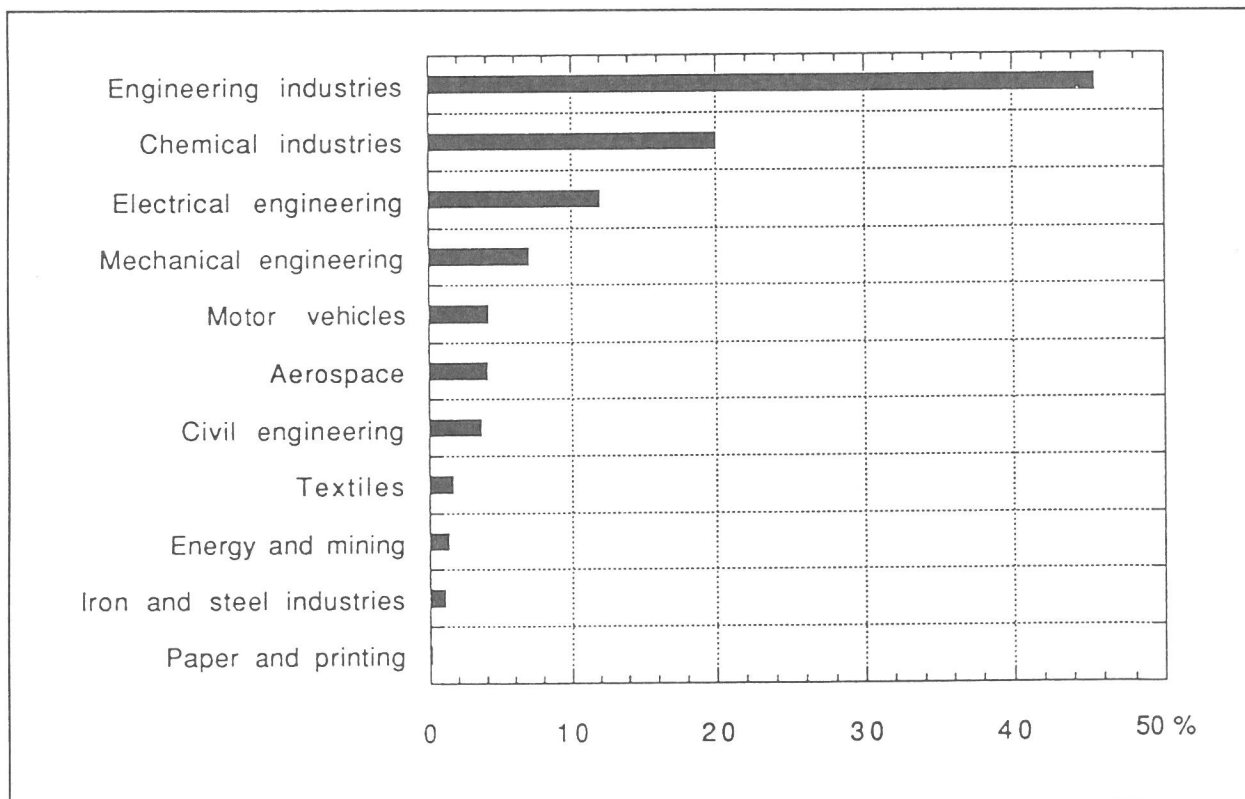


Figure 4.1 Industries interested in research and development (928 entries = 100 %)

Other specific industries - which contribute to about 50 % of the response of the questionnaires were summarized under the general term "engineering industries".

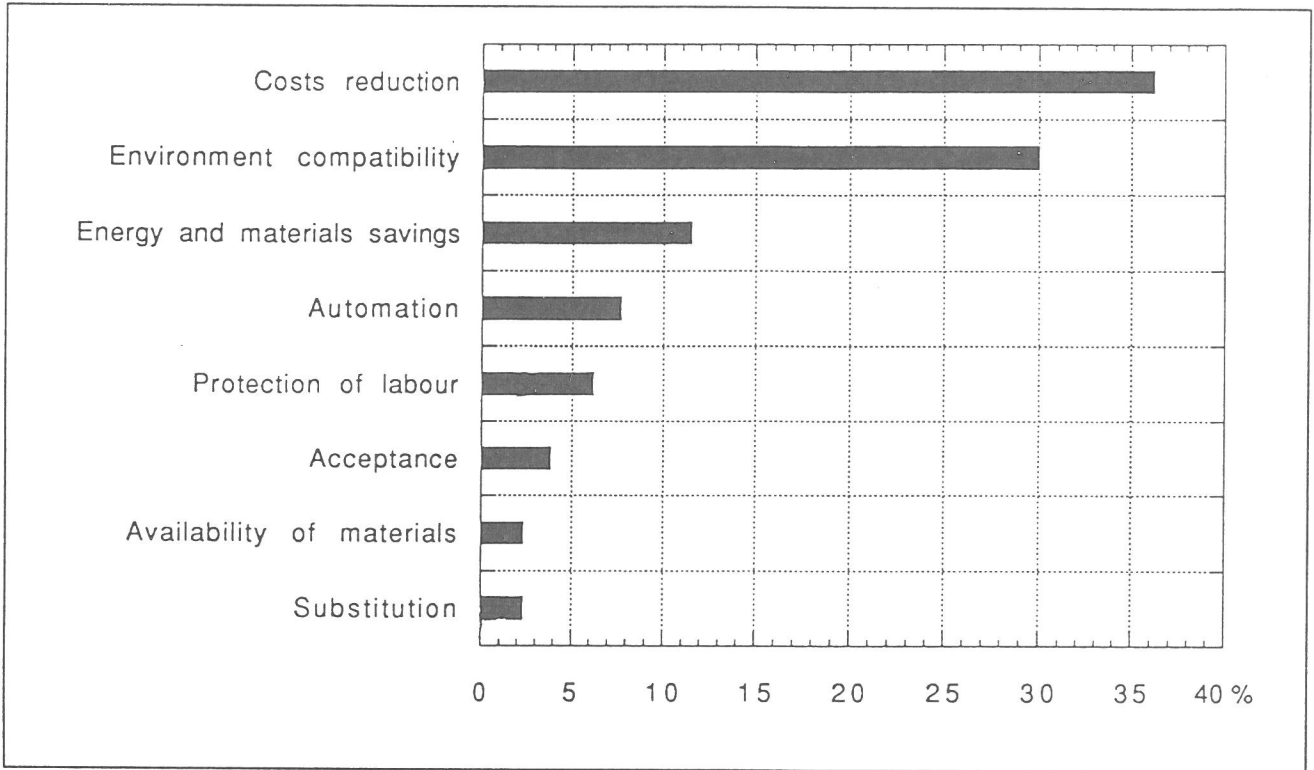


Figure 4.2 General tasks for research and development in industrial and materials technologies (130 entries = 100 %)

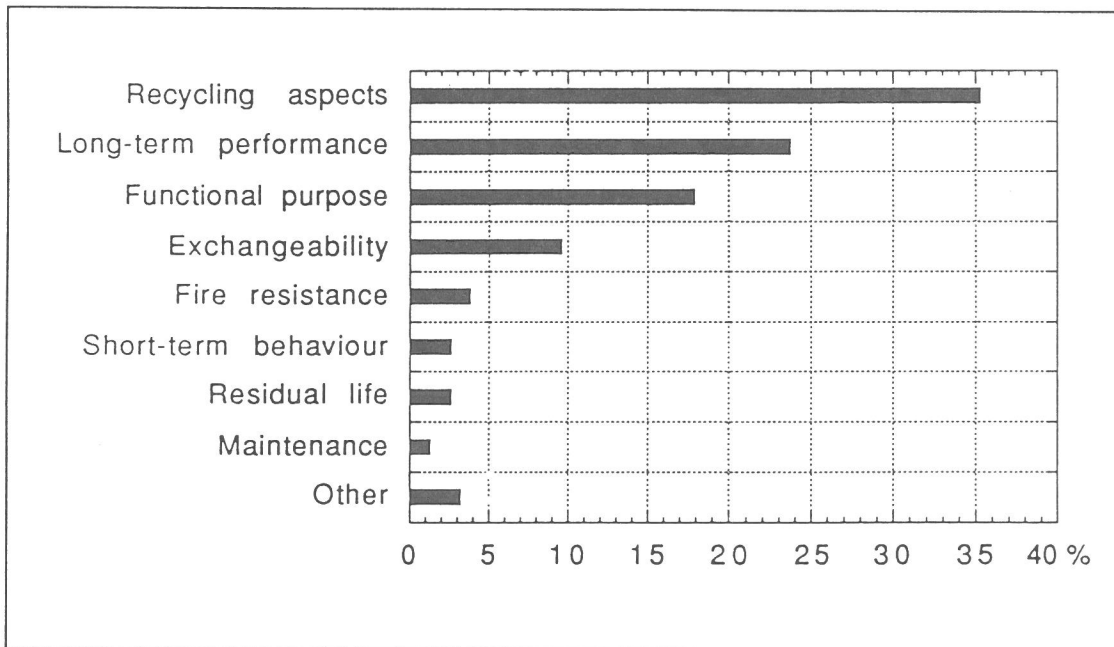


Figure 4.3 Products characteristics suggested for research and development (156 entries = 100%)

The general tasks which have been named by the various industries as priority themes for research and development in industrial and materials technologies are summarized in Figure

4.2. Three quarters of all answers are related to the following topics of overall (medium-term) importance:

- Cost reduction
- Environment compatibility
- Energy and materials savings.

For the industrial products which may result from intensified R&D, the following topics are of paramount importance (response of about 80 %) as can be seen from Figure 4.3:

- Recycling aspects
- Long-term performance
- Functional purpose

## 4.2 Materials and materials properties suggested for R&D

In the field of materials, the main interest is in composites (30 %) followed by ceramic materials (20 %), metals and alloys (19 %) and polymers (17 %), see Figure 4.4. The main materials properties suggested for R&D are compiled in Figure 4.5.

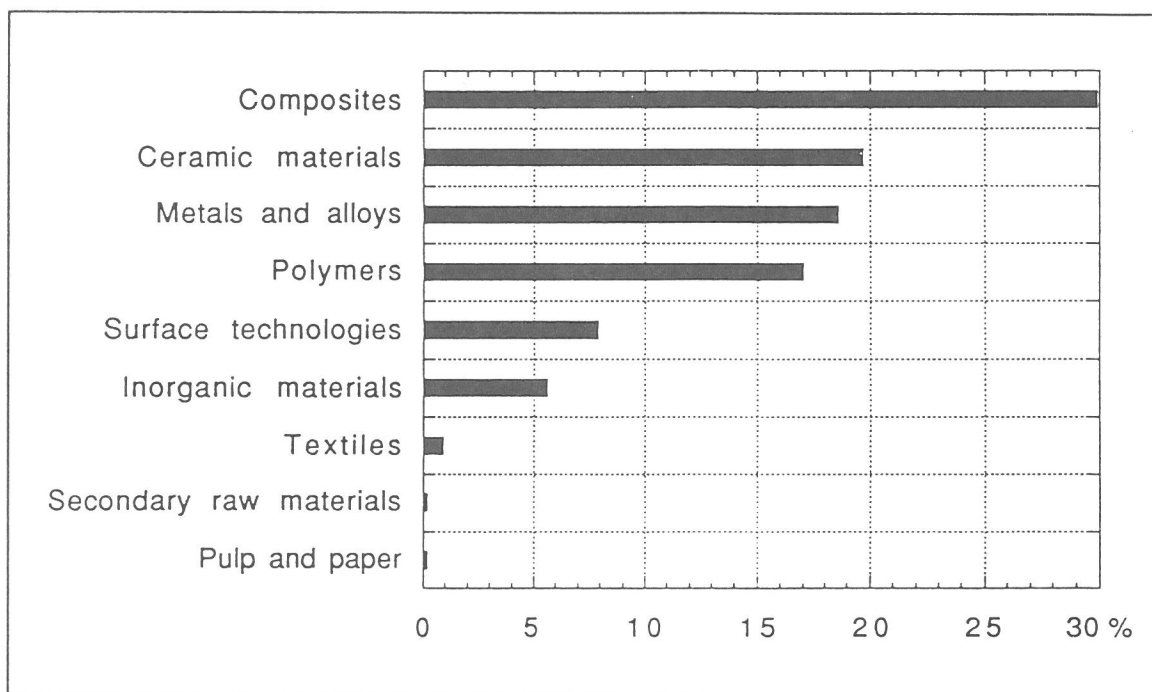


Figure 4.4 Materials suggested for research and development (596 entries = 100 %)

With respect to materials and materials properties suggested for future R&D in Europe, a large variety of details was given in the questionnaires. For the main classes of materials mentioned above, the themes which correlated in substance are listed below in an approximate order of importance.

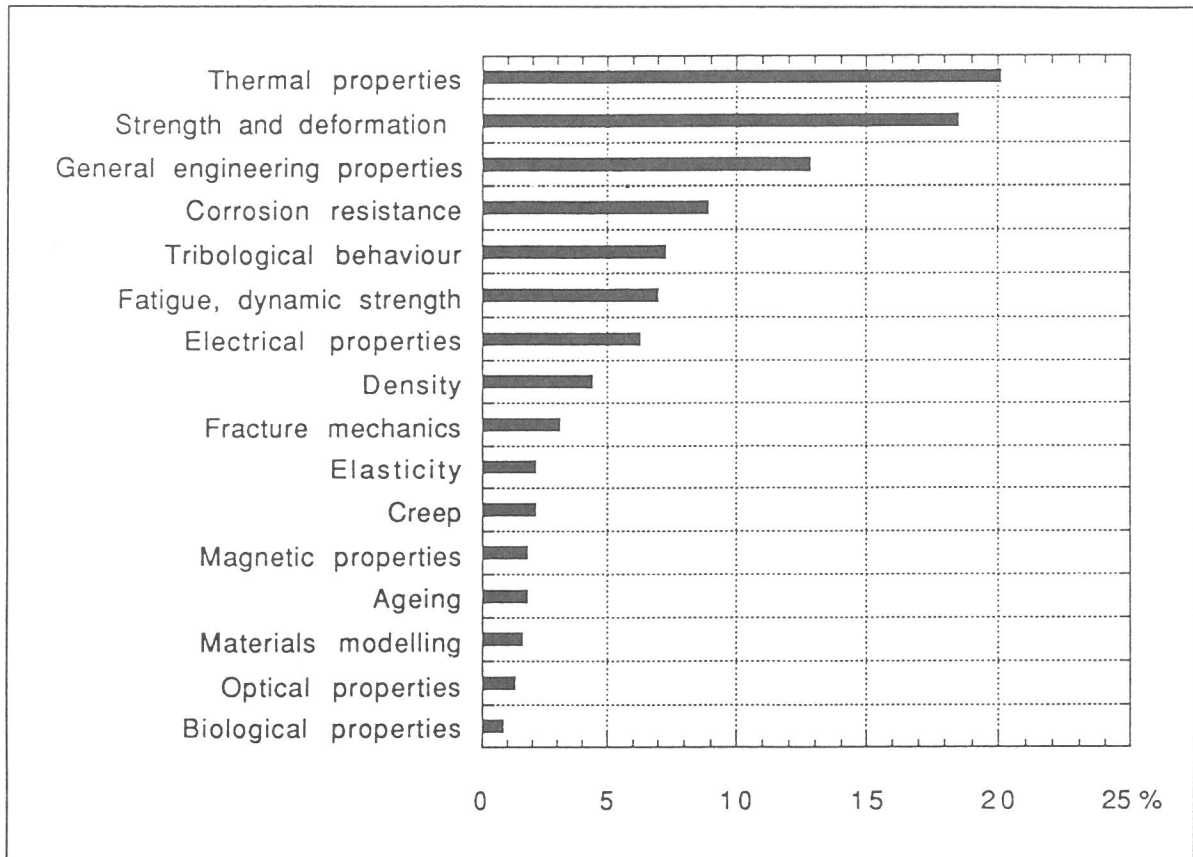


Figure 4.5 Materials properties suggested for research and development (383 entries = 100 %)

#### 4.2.1 Composites

For the present purpose, it is reasonable to subdivide the entries for the total class of composites (100 %) into those for polymer matrix composites (47 %), metal matrix composites (15 %) and ceramic matrix composites (7 %). The remaining percentage is attributed to concrete composites and other general entries which have not been specified. In detail, the following themes are of interest:

**(a) Polymer matrix composites (PMC):**

- High temperature performance
- Increased stiffness and low density
- High strength and fracture toughness, improved damage tolerance and compressive properties
- Improved resistance against aggressive agents.

The following types of PMC have been mentioned for special interest:

- Thermoplastic matrix composites
- Composites with short fibre and sub- $\mu\text{m}$  reinforcement as well as those in the molecular range

- Composites with whisker reinforcement
- Composites for low temperature processing.

Additional indications with respect to an improvement of the mechanical properties are expected from investigations on:

- Effects of fibre alignment as well as on
- Fibre-matrix interface properties, e.g. the debonding effects.

**(b) Metal matrix composites (MMC):**

Prominent themes are:

- Al-matrix composites with ceramic fibres; upgrading of strength and stiffness;
- Compounds with a combination of high strength and good corrosion resistance;
- Compound materials and structures with special properties profiles.

Again, the effect of fibre alignment on the mechanical properties is of interest.

**(c) Ceramic matrix composites (CMC):**

Themes of special interest are:

- Resistance against high temperature and chemical attack and
- Upgrading with respect to strength, fracture toughness and damage tolerances.

Of further interest are the reinforcement with whiskers and other short fibres as well as the effect of the fibre alignment and that of the interface properties on the debonding of the fibres.

#### **4.2.2 Ceramic materials (monolithic engineering ceramics)**

For the class of monolithic engineering ceramics, an upgrading with respect to the following aspects is of general interest:

- Strength in general
- High temperature properties with respect to strength, creep resistance and inhibition of grain growth
- Brittleness and fracture toughness
- Fatigue strength
- High temperature corrosion resistance
- Resistance against chemical attack
- Tribological behaviour (friction, wear)

Out of the variety of engineering ceramics, the class of non-oxide ceramics (SiC, Si<sub>3</sub>N<sub>4</sub>, B<sub>4</sub>C, BN) seems to be of special interest, whereas the necessary improvement of the reliability of ceramic structures in general leads to further R&D activities in the fields of powders and agglomerates (< 1 µm) as a basic material for engineering ceramics. In this context, the surface chemistry of the powders and the manufacturing and application of "nanomaterials" is discussed.

Further ceramic materials of interest for R&D activities are:

- Functional ceramics with special electrical, magnetic and optical properties,
- Ceramic coatings,
- Glass and glass ceramics with respect to an upgrading of strength and toughness,
- Refractories for melting furnaces etc.
- CERMETS (ceramic/metal compounds).

As a general R&D theme, the development of proper constitutive models for the deterioration mechanisms of brittle materials was recognized.

### 4.2.3 Metals

Of special interest for R&D activities are those metallic materials which promise further upgrading of the high temperature behaviour (strength, creep resistance, high temperature corrosion resistance) for application in gas turbines, jet engines, chemical processing lines etc.:

- High temperature steels
- High temperature superalloys of the polycrystalline, directionally solidified and single crystal type
- Mechanically alloyed (MA) Ni-base alloys
- Intermetallics, e.g. of the Ni-Al-type for high temperature application
- Ti-alloys for the medium temperature range.

Further activities are desired with respect to an upgrading of low density metals such as:

- Mechanically alloyed Al- and Ti-alloys (strength at higher temperatures)
- Al-Li-alloys for the aircraft industry (density, stiffness)
- Li-alloys (extreme low density).

Nanocrystalline metals and amorphous alloys manufactured by rapid solidification techniques are, furthermore, prone to further research.

For a plurality of conventional materials, an improvement is requested especially with respect to economical effects and competitiveness:

- Micro-alloyed steels with respect to an enlargement of the field of application; acceptance in regulations
- Cast metallic materials by advanced processing routes; easy recycling
- Austempered nodular cast iron
- Duplex-structure stainless steels
- Materials and structures via powder metallurgy routes; higher relative density
- Metals with superplastic properties
- Magnetic alloys with minimized losses.

And, finally, further research on the correlation of microstructure and mechanical properties has been recognized as a general future task.



#### 4.2.4 Polymers

For the class of polymers and polymer blends, one of the main themes of interest for R&D is focussed to an upgrading of the properties at higher temperatures:

- Flow (creep) resistance at elevated temperature,
- Thermal resistance (e.g. at soldering temperatures)
- Hydrothermal stability
- Thermal conductivity
- Fire resistance without use of halogen elements.

Importance is also attributed to the electrical conductivity - especially reversible (switch on/off) - as well as to low electrical charging. Strength and toughness are generally upgrading candidates for polymers. Other properties such as:

- Chemical endurance and resistance against aggressive agents
- Low coefficient of friction and high wear resistance
- Special optical properties

are of special interest, whilst good biological degradability and recycling properties are of vital importance for future application of this class of materials.

R&D activities are necessary also for polymer biomaterials (engineering inside the body). With respect to this application "tailor-made" materials with suitable mechanical properties, no degradation inside the body and no release of toxic monomers are required.

Quite different properties are important for polymer materials which are optimized with respect to an application in the textile and shoe industry. Low density, high damping capacity and wear resistance as well as special porosity are required here.

#### 4.2.5 Other materials

In addition to the R&D topics with respect to the four main materials classes, suggestions for R&D concerning other types of materials have been made as outlined in the following:

- Materials for information technologies: Microelectronics, circuit boards; materials with integrated optics; high purity materials of special composition for the computer technology; substrates for thin coatings; semi-conductors with diamond structure

Coating materials: Coatings made from hard materials (wear resistance); ion implantation, laser hardening; sputtered thin coatings for the computer technology, impact resistant coatings; functional coatings of high surface performance and corrosion resistance

- High temperature superconductivity materials (HTS): Application for energy technology (coils, magnets etc.); high critical current density; compound systems of HTS ceramics on metallic substrates; processing of HTS powders to wires
- Materials for civil engineering application: Concrete with composite cements and polymer additives and fibre reinforced micro-concrete (glass and steel fibres)
- Carbon materials and carbon fibres for composite materials
- Polycrystalline diamond with increased electrical conductivity and improved thermal properties; application for coatings
- Materials for catalytic processes.

### 4.3 Design techniques suggested for R&D

For the area of design, the order of quantity of entries in the questionnaire is given in Figure 4.6. It illustrates that material-related concepts are of great importance (50 %), whereas computer aided techniques (CAD, finite elements calculation, expert systems etc.) and general design rules are recognized as being of equal significance. In the following, the key words again have been listed in an approximate order of importance.

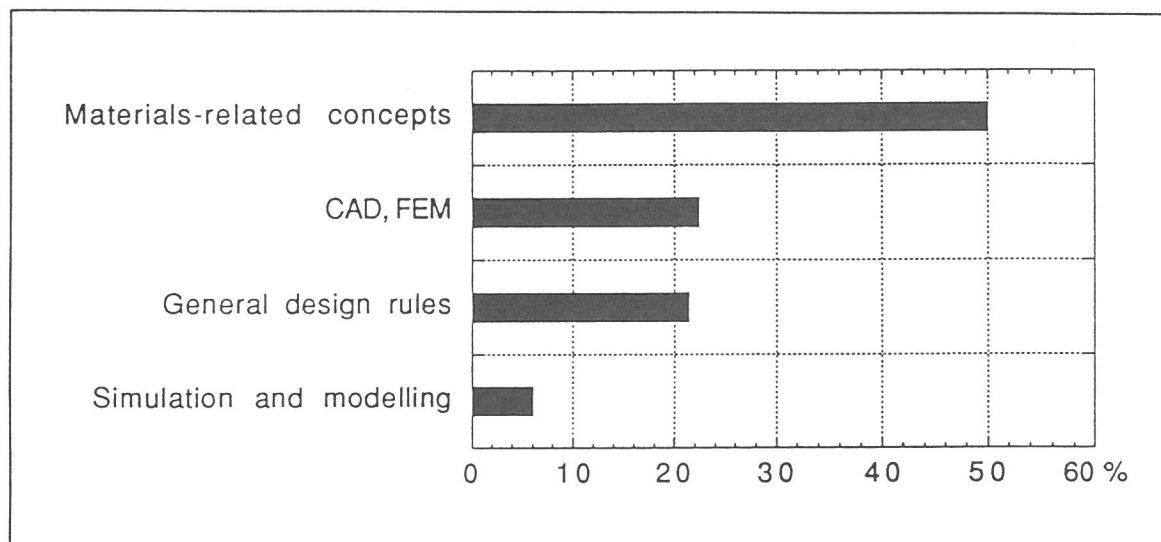


Figure 4.6 Design techniques suggested for research and development (134 entries = 100 %)

#### (a) Material-related concepts:

- Transfer of materials properties from specimens to components and structures; influence of geometry, down-sizing and up-sizing
- Special design of components made out of short-fibre reinforced composites
- Design of compound components; polymers combined with other materials. Advanced sandwich components and cellular structures with high stiffness
- Design of micro-mechanic components out of polymers
- Design strategies with respect to brittle materials (ceramics); critical points of load introduction
- Probabilistic approach to design; reliability models; distribution functions of material properties
- Material flow calculations for improved design of metal forming moulds

#### (b) Computer aided techniques:

- Improvement of the efficiency of CAD as a basis for increased application; better adaptability of CAD systems
- Application of finite element methods (FEM) for an assessment of strength, life time, and safety; use of material models for deterioration and failure
- Improvement of the application of expert systems for design and the assessment of life time and safety.

(c) General design rules:

- Considering total life of components and structures, including defuncting and recycling
- Design with respect to manufacturing routes, mainly energy saving processes
- Design with respect to damage tolerance, maintenance, supervision, and quality control

Especially in the field of high temperature components, there is a need for improved material modelling which is compatible with the microstructure situation in a wide range of temperature and mechanical loading or deformation.

Other more special themes compiled from the questionnaires are:

- Low weight design with respect to the dynamic behaviour of components
- Design with respect to coating processes and coating performance
- Global service life assessment for building and components
- Seismic design in civil engineering

#### 4.4 Manufacturing and processing technologies suggested for R&D

In this field, 24 % of the respondents suggested an improvement of general manufacturing technologies. Quantities in the range of 6...12 % of the entries demonstrate interest in further R&D in quite conventional fields of manufacturing and processing technologies as casting, forging, joining, forming, and machining. Similar percentages are related to some advanced technologies as computer integrated manufacturing (CIM), mass production techniques, and powder metallurgy. A survey of the interests is given in Figure 4.7.

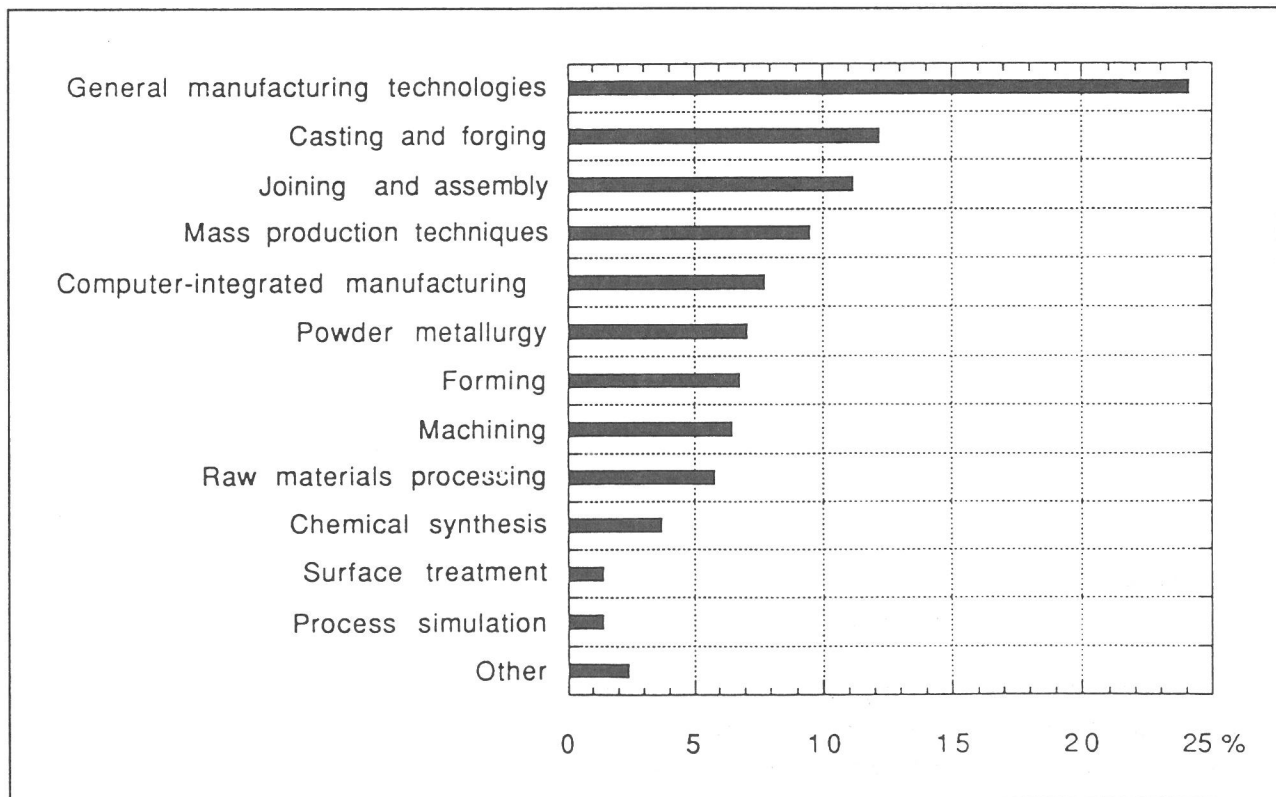


Figure 4.7 Manufacturing and processing technologies suggested for research and development (294 entries = 100 %)

Further research and development of manufacturing and processing technologies must be seen in connection with the pertinent materials or products. Therefore, the key words out of the questionnaires are compiled with respect to the main material classes. Again, the details are listed in an approximate order of importance given by the number of entries.

#### (a) Polymers

In the field of forming, joining, moulding, and other manufacturing techniques, the following details are of interest mainly with respect to economical effects:

- High speed injection moulding with high accuracy; in this context, the rheology during mould charging is important
- Miniaturization of injection moulding for small electronic structures
- Electrochemical forming and machining; machining and laser cutting
- Manufacturing of very thin structures and multiple layer structures
- Deep drawing and stretch forming of polymers
- Improvement of prepregging techniques; extrusion with prepregs
- Three-dimensional fibre preforming
- Rationalization by combination of chemical reaction and extrusion; reaction injection moulding for thermoplastic material

Some further problems with respect to manufacturing of polymer materials are:

- the glueing and snapping techniques and
- the improvement of rapid prototyping of components out of polymers.

Related to R&D activities in the field of synthesis and raw material processing are keywords such as:

- Polycondensation techniques
- Electropolymerization
- Electrocoagulation
- Rheological processes in the molecular range
- Electrostatic deposition

Of interest are, furthermore, improved possibilities of a recycling of thermoplastic composites to moulding processes.

#### (b) Engineering ceramics

For this class of material, the raw material processing is of predominant effect on the component properties. Some details prone to R&D are:

- Pure powders with narrow particle size distribution
- Sol-gel-techniques
- Organo-metallic processes for powder production.

An upgrading of all joining techniques (ceramic- ceramic and ceramic-metal) also for high temperature service is of vital importance for an increased application of ceramics. Besides that, the basic manufacturing techniques have to be further developed. The following key words give some detailed information compiled from the questionnaires:

- Wet forming techniques
- Optimized paste for extrusion and for injection moulding
- Economical sintering processes and sinter/HIP-techniques
- Manufacturing routes for components free of internal defects
- Techniques for the production of ceramic matrix composites with longer fibres
- Machining of ceramics.

Another field still under development is that of ceramic material with well defined porosity in a wide range for high temperature filtration, combustion, catalysis etc.

### (c) Metals

In the field of metals and alloys conventional manufacturing processes such as casting, forging and metal forming are included in approximately half of all entries in the questionnaires and demonstrate the importance of a further improvement of these wide spread techniques with respect to economical competitiveness. Next in the range of importance are mass production and CIM as well as powder metallurgy and joining problems. Out of the variety of key words in the questionnaires, the following have been selected:

- Die castings and injection die casting
- Continuous casting of thinner flat, bar and wire materials combined with rolling; near net shape casting
- Thin walled extrusion
- Rapid forming techniques which result in special properties of metals.

For metal matrix composites (MMC), casting techniques are of interest as well as forming and machining procedures which do not result in a deterioration of the material. Low cost large series processes for the manufacturing of MMC in general are open for further R&D efforts. An upgrading of powder metallurgy was mentioned, too, especially with respect to economical benefits. In this context, atomizing techniques of the base material are important with respect to the effect on the components. A still important question is the effect of joining - especially welding - on the properties of components. Special welding techniques, e.g. diffusion and friction welding, are themes for further development as well as soldering techniques. Of special interest is safe welding for corrosion resistant materials. In the field of machining, the effect of material composition on the machinability and on the accuracy of the components was mentioned as interesting. Finally, problems out of the field of rapid solidification techniques (RST) with respect to the manufacturing of powders, foils and wires with special properties have been mentioned in the questionnaires. Attributed to these "base materials" all possible techniques of compaction are themes for R&D.

### (d) Manufacturing problems in the field of civil engineering

In this field, some details for further R&D have been compiled from the questionnaires which could be of general interest:

- Manufacturing of thin structures out of reinforced concrete by vacuum sucking
- Repair strategies for old/damaged structures
- Water jet pressure cutting of rock material
- Robotization of building techniques

#### (e) General manufacturing problems

Some general problems, not related to special classes of materials, but more or less applying to the total manufacturing technology are partially included in Figure 4.7 under the designation "general manufacturing technologies". Some problems of this field are characterized by the following key words:

- Manufacturing process modelling
- Manufacturing just in time, important for mass production
- Processing with reduced environmental impact and low energy consumption
- General effects of manufacturing routes on the material and component performance
- Standardization of NC-control devices
- CIM with artificial intelligence
- Man free production
- Tools of high wear resistance for long service life and high machining accuracy
- Advanced manufacturing techniques: e.g. fluid jet cutting, high speed cutting etc.

### 4.5 Testing and evaluation

In order to improve the competitiveness of industrial products and related technologies, advanced testing and assessment techniques are needed. As can be seen from Figure 4.8, the main interest in this field is in techniques for quality control and non-destructive testing and evaluation (NDT). Another remarkable portion of interest is focussed to R&D with respect to standardization of test methods and process control.

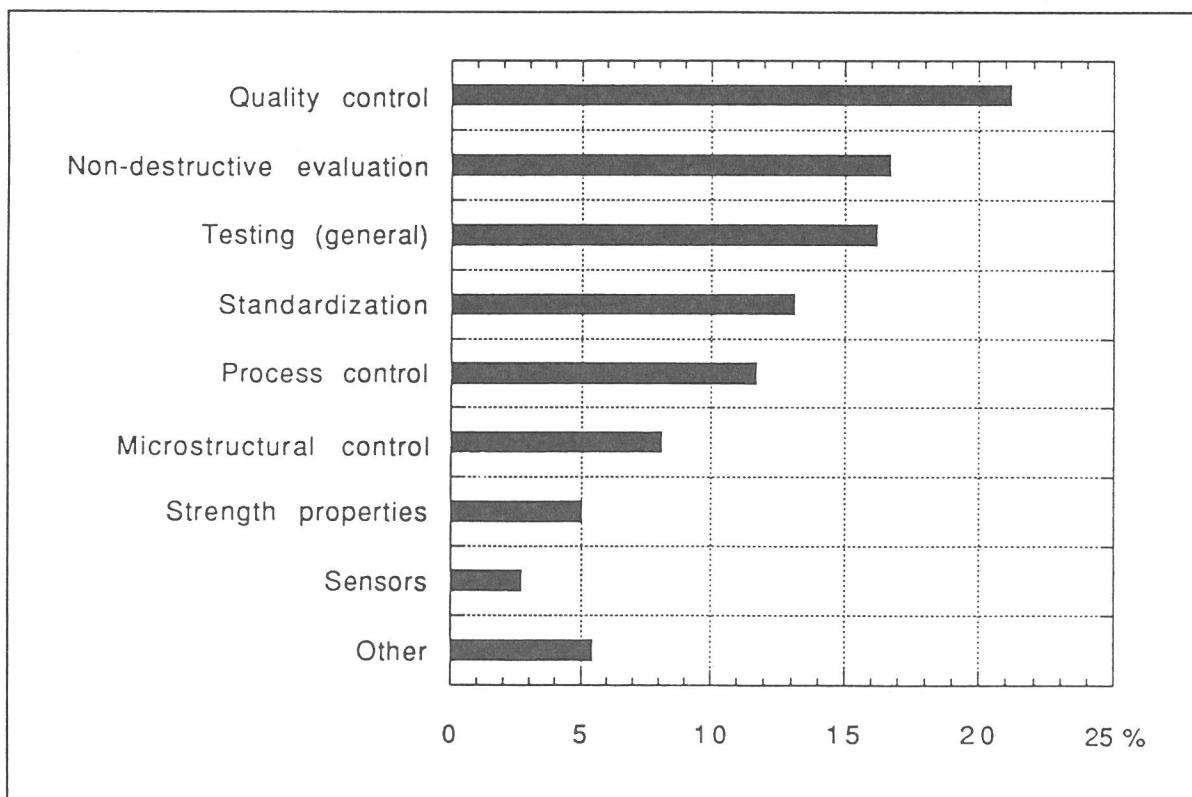


Figure 4.8 Testing and assessment techniques suggested for research and development (200 entries = 100 %)

### (a) Materials-related aspects

Most of the entries in the questionnaires are not related to special materials or products but are of general type. Nevertheless, the non-generalized information is also presented here including the following details:

- For the class of metallic materials, a necessary further standardization is suggested to "advanced" test methods such as:
  - Fracture mechanics and testing of brittle materials,
  - Formability tests with sheet materials,
  - Crack initiation and propagation tests,
  - Random fatigue loading and life time assessment,
- For engineering ceramics, developments of methods for conventional strength properties (specimens and components) are of interest as basis for a standardization of long time behaviour.
- For ceramics, testing during the total route of manufacturing including powder processing, moulding the green compacts and the sintered components seems to be advantageous.
- Testing of the high temperature corrosion resistance is another key word for metallic and ceramic materials.
- Appropriate test methods are still needed for composites, especially for fibre reinforced polymers.
- Some entries are related to an improvement of (low cost) non-destructive testing (NDT) with respect to:
  - Polymer matrix composites and polymers
  - Engineering ceramics components before and after firing (on-line NDT).

### (b) General aspects of testing

Focal points for R&D in the field of general testing and evaluation can be named as follows again in an appropriate order of importance:

A dominant importance is attributed to all on-line quality control routes, manufacturing integrated control systems (process control) and computer-aided control procedures. This includes:

- Laser based metrology and control
- Computer aided image processing (surfaces)
- Development of sensors for various physical properties of materials and components
- Development of the automatization of the testing.

The application of all methods of non-destruction testing (NDT) is of special importance with respect to quality control, it contributes to other fields of more basic R&D such as

- NDT for the evaluation of mechanical properties of materials
- Testing of bonding effects of composites and compound structures.

With respect to the strength of materials and components the following key words have been compiled:

- Testing under complex stress states
- Scale tests with respect to actual service conditions
- Short time tests and long service time performance evaluation of materials and components
- Early detection of damages; remaining service time
- Detection of deterioration by aging
- Strength of glueings
- Analytical methods for an assessment of residual stresses.

With respect to other important properties or products the following details have been found in the questionnaires:

- Improvements of tribology tests including standardization
- Tests for a characterization of pore structures; permeability for gas and liquids, e.g. for porous ceramics
- Further development of acoustic emission testing methods
- Testing and modeling of anisotropic behaviour materials

Special problems are arising with respect to the testing of micro-electronic bondings and solderings, and in the field of civil engineering, where two further problems have been mentioned:

- In-situ assessment of the performance of civil engineering structures
- Testing methods for fibre reinforced, foamed and repair mixtures of concrete.

## **4.6 The need for an integrated processing/properties/ performance approach**

In the approach to upgrade existing materials and to develop new materials and products it must be recognized that the aspects of "processing", "properties" and "performance" are closely linked with each other. In a summarizing manner these aspects are compiled in the Figures 4.9 to 4.12 for the main materials classes, namely composites, ceramic materials, metallic alloys and polymers. Again, this compilation is based on the results of the questionnaire enquiry.



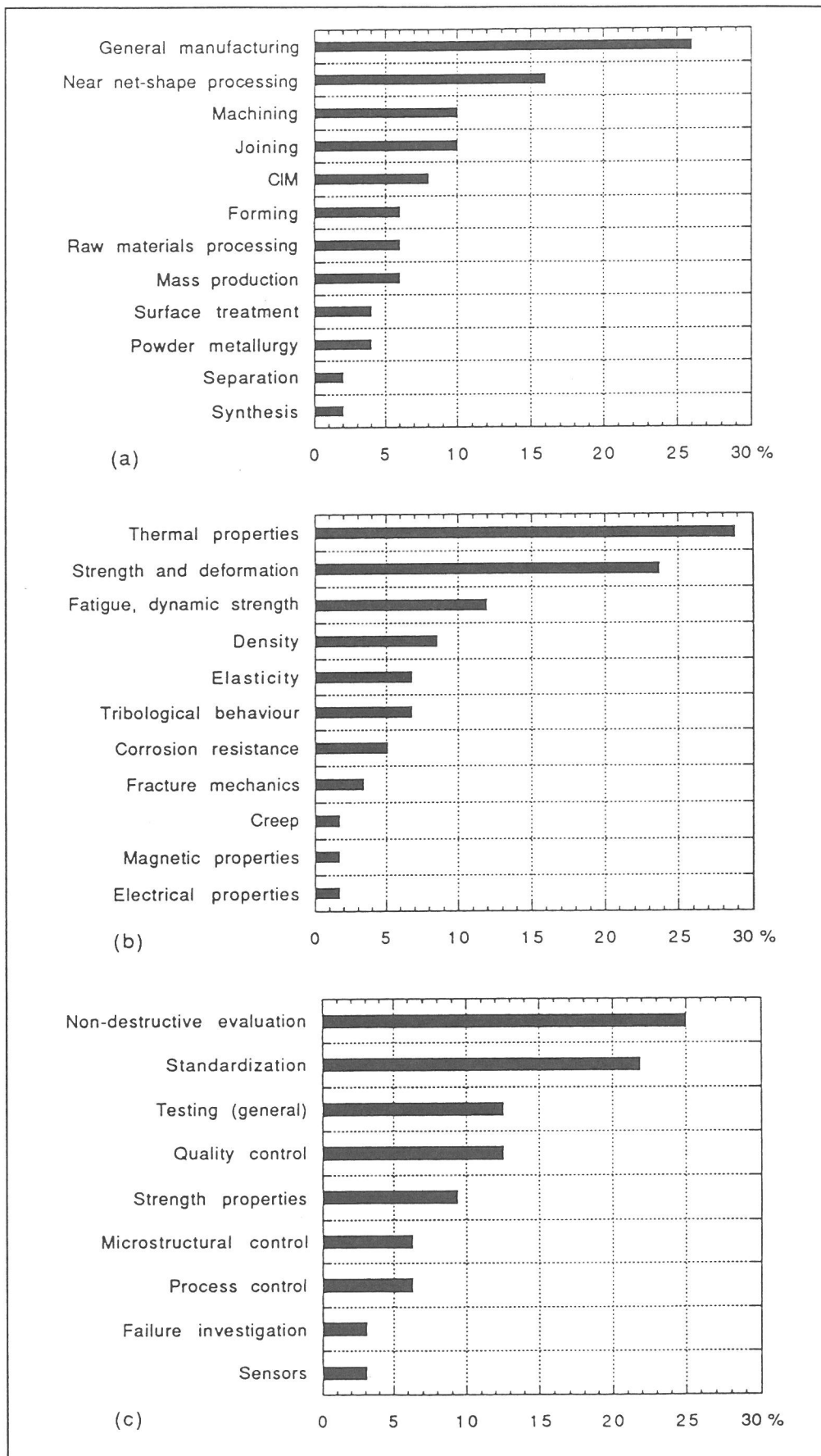


Figure 4.9 Research and development suggestions for composites: (a) Processing and manufacturing, (b) Properties, (c) Performance and testing

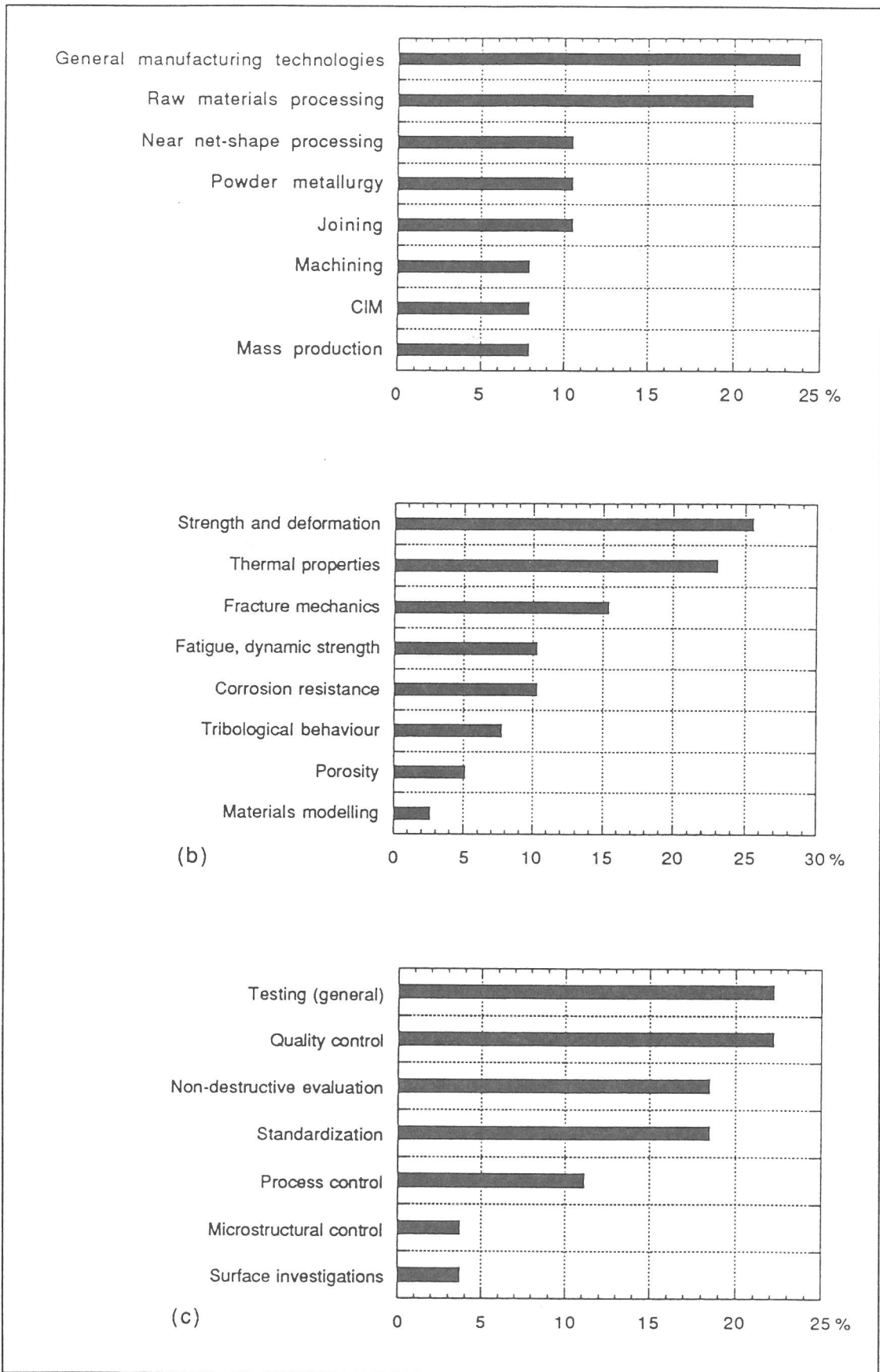


Figure 4.10 Research and development suggestions for ceramic materials: (a) Processing and manufacturing, (b) Properties, (c) Performance and testing

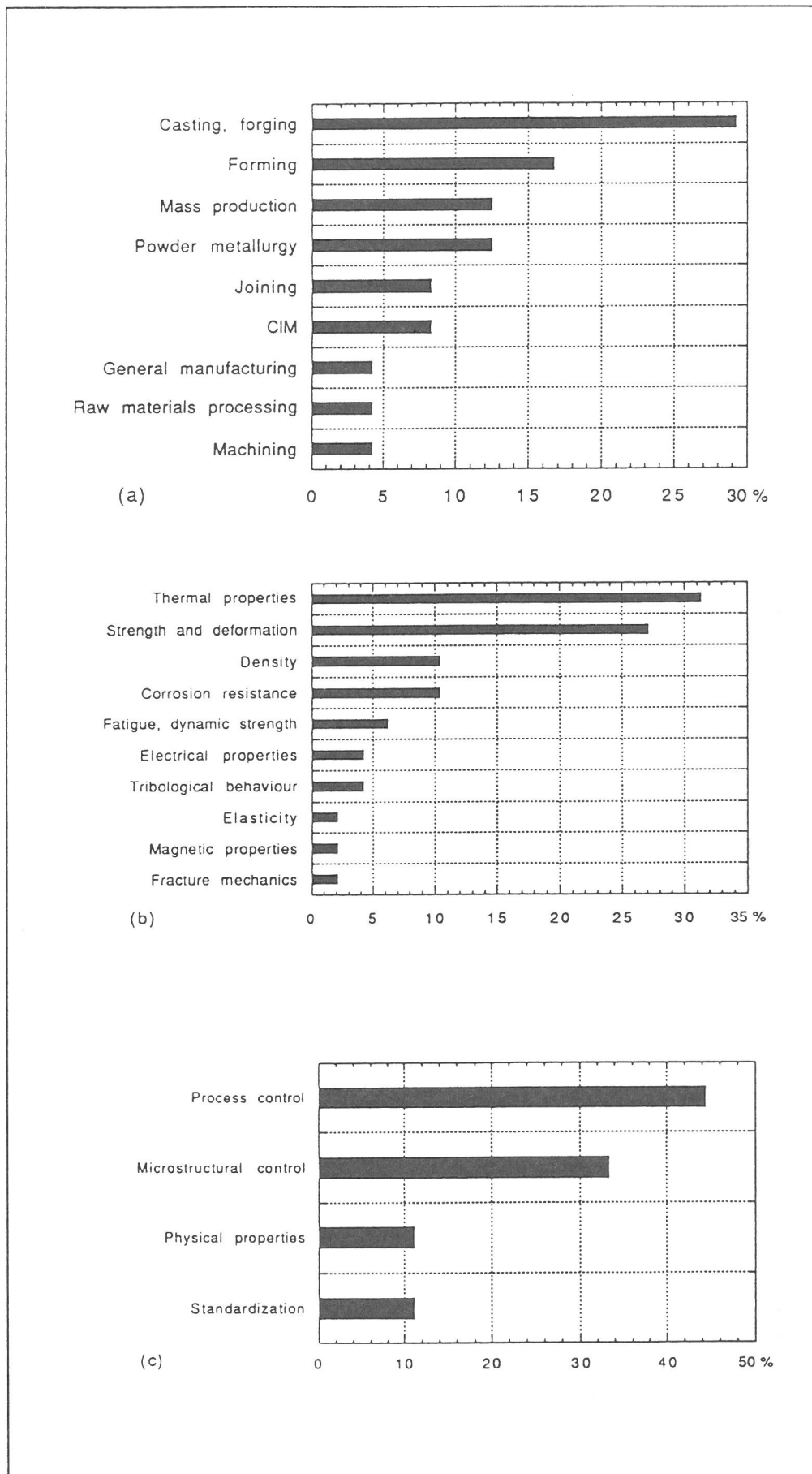


Figure 4.11 Research and development suggestions for metallic alloys: (a) Processing and manufacturing, (b) Properties, (c) Performance and testing

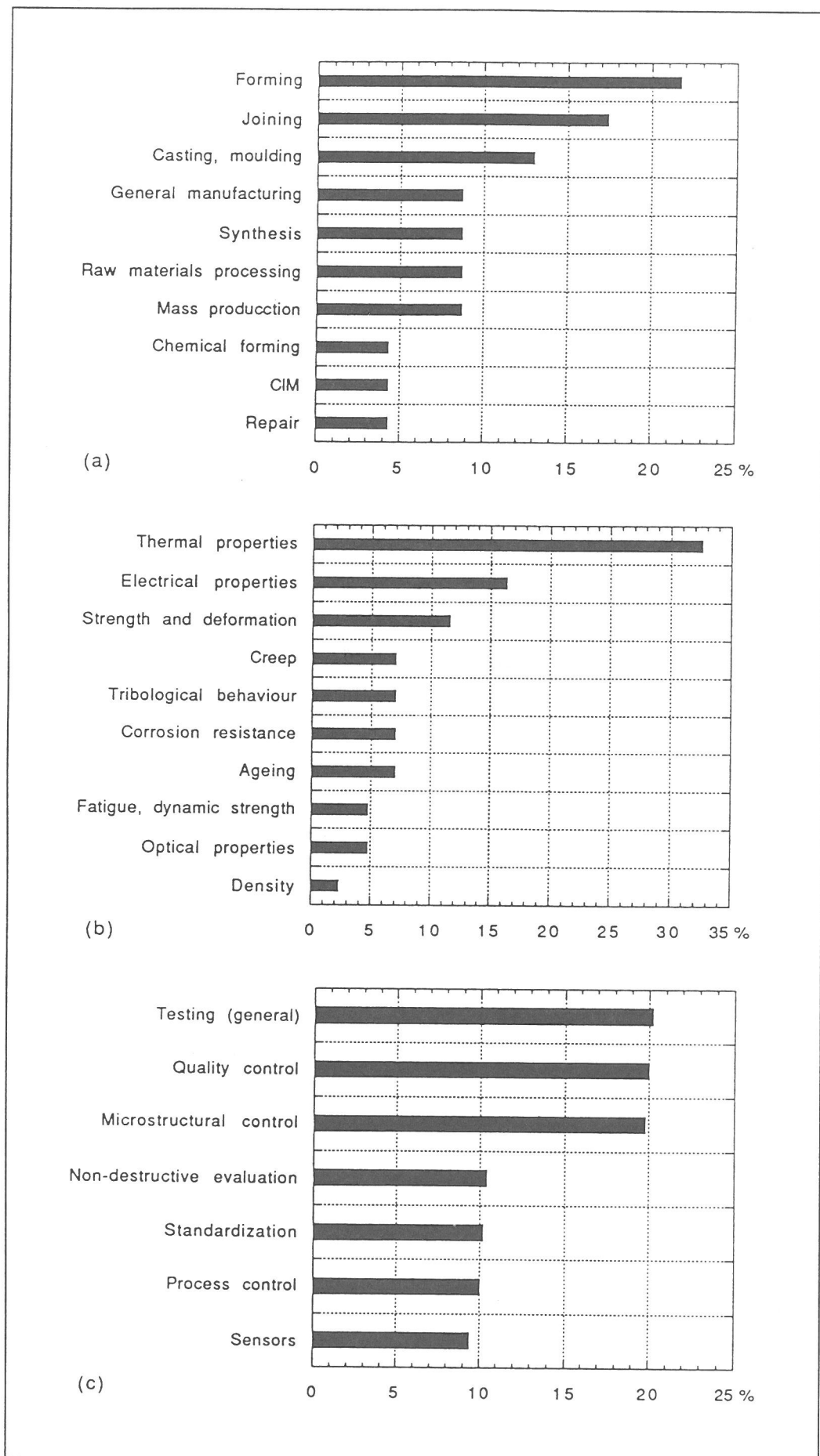


Figure 4.12 Research and development suggestions for polymers: (a) Processing and manufacturing, (b) Properties, (c) Performance and testing

## 5. Research and development trends and needs: Results of discussions with experts

In addition to the enquiry by questionnaire, interviews with experts of the countries of the European Community were held in order to analyse details of R&D needs in industrial and materials technologies. The interview partners from the industry represented mainly the following industrial sectors: aircraft and aerospace, automobile, building and civil engineering, ceramics, chemical engineering, electrical engineering, electronics, instrument engineering, iron and steel, machinery, mechanical engineering, powerplants. The experts from universities and research institutes represented the various sectors of materials science, engineering and testing as well as design and production technologies.

As an omnipresent demand, a quicker transfer of R&D results to industrial applications was recognized. Sometimes - e.g. for a "new" product - a successful and competitive demonstration activity can act as a push top-down to the industry. However, in general there exists a large awareness of the potential of new materials and manufacturing techniques.

As reasons for the undoubted success of some Japanese industrial activities the following aspects were mentioned:

- better organization of the production
- higher degree of automatization
- more robotization
- smaller fabrication units with local build-and-buy-approach
- factory automation instead of bottom-up computer integrated manufacturing (CIM).
- high availability of the manufacturing lines by quality and reliability
- openness for R&D results and willingness for unconventional technical applications.

All interview partners unanimously agreed in the necessity of recognizing environmental and human aspects in all fields of technology from the beginning of new activities. This includes material and energy saving techniques as well as optimal recycling possibilities and acceptable disposal. These aspects as well as an arrangement of manufacturing routes recognizing human needs and public regulations will get more importance.

The main results of the consultations with the experts are compiled in the following with respect to four basic technical areas:

I. Materials Technologies

II. Design

III. Manufacture

IV. Testing and Assessment

## 5.1 Technical area 1: Material Technologies

### 5.1.1 Ferrous materials

#### (a) Iron and steel

Iron and steel are still the most widely used - and recyclable - classes of materials in a broad variety of industrial branches. General themes for R&D in the area of iron and steel materials are:

- development of processes for cheaper production of optimized materials in general, improvement of the reliability of the manufacturing routes with respect to the material properties
- materials of high purity and homogeneity with finer microstructure
- materials with improved machinability, formability and optimized properties for subsequent treatments.

#### (b) Metallurgy and fabrication

As main factors with respect to further development of iron and steel materials, the following matters have been recognized:

- continuous casting processes avoiding re-heating; the necessary subsequent forming ratio for high quality final material is still an open question. Smaller near net-shape slab dimensions as preliminary sections for the rolling of bars, rods and sheet material
- improving horizontal continuous casting processes
- secondary metallurgy as prerequisite for optimized materials
- increasing application of thermo-mechanical (TM) treatment including quenching processes for steels with a large variety of strength, toughness and weldability; economical use of expensive alloying elements.

With regard to special products, high strength sheet materials are of increasing interest for the automotive industry. For these dual or 3-phase (ferrite, bainite, martensite) or micro-alloyed materials good formability and weldability (spot welding, laser welding) as well as good paintability and corrosion resistance are of importance. "Bake hardening" effects shall be used for an additional strengthening of these materials.

Very thin packing plates require a maximum homogeneity of the processing routes. And this is the case for magnetic grain oriented sheet material too. An interesting alternative could be the electrolytical deposition of thin sheet material.

#### (c) Semi-finished products

For rod, bar and plate material there is still a deficit with respect to an application of TM high strength steel material. In the civil engineering, pressure vessel and joining technologies, some demonstration projects are necessary to improve the acceptance of these grades and to introduce it to the pertinent regulations. In the field of heat treatable steels, e.g. semi-finished forged products for the automotive industries, alloyed steels should be replaced by unalloyed or microalloyed steel grades. Economic requirements in the mass commodity production results in a strong competition between forged components and those produced out of cast iron with nodular graphite.

For tool steels an increasing portion of manufacturing by powder metallurgical routes is expected, whilst for roller bearings material lower costs are necessary by application of continuous casting procedures. For the class of corrosion resisting steel an increasing importance is expected for austenitic-ferritic -("duplex") steel grades.

Under discussion are manufacturing and application of metallic glasses and nanocrystalline iron materials. The latter are of special interest because of their potential high homogeneity and exceptional mechanical and physical properties.

Of some interest are treatments by which the deterioration of the material at special service conditions can be eliminated and at least a partial recovery is possible. As an example the neutron flux embrittlement of steel is mentioned.

#### **(d) Surface treatment of steel products and components; clad material**

A main goal of surface treatment of steel is corrosion protection. Usual zinc coatings (hot dipped galvanized or electrolytical) will be substituted by improved coatings of alloys and other metals (Ni, Zn-Cr, Al-Zn, Cr-oxide), multi-layer coatings or compounds (Zn and ZnO). Themes of R&D-interest are the coating adhesion mechanism, the homogeneity and the defect distribution of coatings. Coating techniques must be further developed to arrive at increased corrosion resistance as well as with respect to good performance under joining conditions. In this context, problems at spot welding of coated material (cleanness of the electrodes) are of interest.

For steel-based clad material the extent of applications is still open. On high strength steel material, cladding materials such as corrosion resistant steel grades, aluminium and other metals as well as polymers are used; convenient methods of cladding are rolling and glueing.

### **5.1.2 Non ferrous metals**

Metallic materials for high temperature (HT) applications (gas turbines, chemical processing, etc.) are growing candidates for R&D activities. For power and aeroengines an operation at increased thermal efficiency combined with reduced weight (jet engines), a longer life (creep, fatigue), sufficient high temperature corrosion resistance (sulphur, salt and dust ingestion) and low cost manufacturing are vital points. Improvements of polycrystalline, directionally solidified and single crystal superalloys for turbine blades are still under discussion, whilst turbine components in general are very demanding areas of research. In this context HT-intermetallics of the Ni-Al and of the low density Ti-Al-Type (compressors) with sufficient ductility are of importance. There are hints that the capacity of refractory metals - as alloys too - has not yet been investigated sufficiently.

In the transport and traffic industries there are expected further activities with respect to low density metallic materials. Cast aluminium alloy components (motor blocks, cylinder heads, pistons) continue to increase in application, and more R&D activities are useful for Al-Li-alloys as well as for Titanium and Ti-alloys (Al, V, Zn, Nb) which combine low density, high strength and high corrosion resistance. Production of high purity Titanium is not yet without problems.

Two classes of metallic materials for which an application is not yet fully exhausted are superelastic alloys and shape memory alloys. The latter are prone for use in so-called "intelligent" components, in medical technology, electrotechnical application, sensors and actuators.

### 5.1.3 Engineering ceramics

With respect to monolithic ceramics, the interview partners gave a remarkable large variety of informations about necessary R&D activities. Engineering ceramics seems to be one of the key areas for R&D with potential industrial participation.

Main materials under discussion are - besides oxides - SiC, Si<sub>3</sub>N<sub>4</sub>, borides, sialon and carbon materials. The key problem for R&D is still an improvement of the toughness, e.g. by Zirconia stabilizing of Si-nitride:  $K_{Ic} = 5 > 12 \text{ MPam}^{0.5}$ . Technical beneficial upgrading of the toughness as prerequisite for load bearing components is expected only for fibre reinforced ceramics, e.g. SiC- matrix with SiC-fibres:  $K_{Ic} > 35 \text{ MPam}^{0.5}$ . Until an availability of materials of higher toughness at reasonable costs is provided, the brittleness of monolithic ceramic and the low thermal conductivity (thermal expansion) are hindering a broader application. At the moment the main obstacles to overcome are:

- high costs for most of the advanced base ceramic materials, which do not allow a mass commodity production,
- production routes not yet sufficiently developed for mass production; e.g. injection moulding would be of interest,
- insufficient dimensional accuracy of ceramic components after sintering which should be much better than  $\pm 1 \%$ ,
- long machining duration (5 to 7 times of that of conventional materials) and extremely expensive diamond tools.

Approaches to overcome these obstacles are important themes for R&D activities with respect to industrially relevant improvements of monolithic ceramic materials.

For the moment a broader market for monolithic ceramics is expected for components with special wear resistance properties - with and without lubrication - and for higher temperatures too. Friction and wear problems are important general R&D themes for ceramics. Heat exchanger for temperatures  $> 900 \text{ }^\circ\text{C}$  and high temperature fuel cells are named as additional application areas for ceramics.

### 5.1.4 Polymer materials

With respect to bulk polymers, the interview partners gave various assessments about future applications in mass commodity technologies (motor cars, electronic devices, etc.). For the moment it is not quite clear, what will be in future the competitive situation of polymers as compared with e.g. steel materials especially in the automotive industries because of the cost-effective recycling problems and costs for the polymers themselves. In some technical areas, the weight reduction becomes less important and costs (including those for recycling) are the dominant arguments. Out of the variety of polymers, thermo-plastics qualities are of greater interest than thermo-sets, and an increasing interest of polymer blends is observed.

As a problem for future R&D activities the higher temperature and long time (creep, fatigue, wear) behaviour of polymers is still recognized. Even a demand for better resistance against neutron flux was mentioned. These properties have to be evaluated and presented in a manner suitable for manufacturers and designers, probably via expert systems. For mass commodity fabrication with minor costs, injection moulded polymers have to be suitable for simple sliding bearings and load contact points. With respect to costs, polymer surface finishing is important to get optimal coatings and paintings.



### 5.1.5 Composites

The necessity for further R&D composites was emphasized by many of the interview partners; here the three main classes of materials are included:

With respect to metal matrix composites (MMC) aluminium alloys reinforced with ceramic fibres are key candidates with an interesting ratio of strength and stiffness to density and with improved long term properties e.g. creep resistance. Other matrix metals are Mg, Ti and even steel. As reinforcing fibres Ti- and W-carbides as well as carbon fibres are under discussion. Besides strength and stiffness, improved toughness and corrosion resistance are desired properties. The aerospace industry is one of the main applicants of these high-tech materials. R&D activities should focus to the interface resistance, debonding effects, etc.

For highly loaded high temperature components (e.g. in turbine engines) ceramic matrix composites (CMC) are future candidates. Only this class of material promises sufficient toughness for important ceramic components under high loading. Mainly SiC-fibres have been used but quite different reinforcing materials and geometries in combination with the respective manufacturing routes are the goal of many research activities. Again the bonding between matrix and fibres is of special interest.

For glass matrix and glass-ceramic matrix composites with fibre reinforcement some future applications are suggested mainly at higher temperatures. There seems to be a demand for a better understanding of the micro-mechanics and microcracking of these materials.

Polymer matrix composites (PMC) are a class of material of further increasing application in a broad variety of technical areas; the demand of R&D activities with respect to a better understanding of failure mechanisms and upgrading of the properties seems to be unlimited. Even small improvements - including of course the manufacturing routes - may result in pronounced economical benefits. The application of PMC with thermoset or thermoplastic matrix and glass fibres, steel wires and carbon is no more restricted to ambient temperature; it has been widened to elevated temperatures too.

### 5.1.6 Coatings

Coatings can lead to an enormous upgrading of components and materials, because of the optimized combination with the properties of the substrate material. Coatings therefore are candidates for various R&D activities. Even well-known matrix materials such as steels expands to new applications if used as substrates for "intelligent" combinations with proper coatings. An outstanding benefit results from coatings which combine e.g. wear and corrosion resistance or when a special coating material is added to paints. Generally it will be looked for improvements with respect to homogeneity and buckling of paint coatings and the cleaning of the surface before processing. As an example for conventional coating technologies, the effect of deposition conditions on the performance of hard-chromium coating was named as R&D theme. With respect to the development of galvanizing routes the deposition of new material combinations and alloys is of future requirement. As non-conventional techniques the application of metal-polymer combinations as coating material was also named. With respect to metal coating on polymer substrates adhesion is the most important criterion.

Ceramics for coatings are of increasing importance in several fields of technology and therefore subject to R&D activities. This class of material is used for protection against high temperature corrosion and wear and for use as thermal barrier. For example, valves, pistons and

small tubes have been mentioned as applications. Of interest are ceramic coatings for ductile substrate materials too and as a newer type of coating material cermets have been suggested. For tool materials, the PVD- and CVD-assisted coatings are still of interest for further R&D-activities as well as ceramic coatings on steel tools for high machining speeds.

As a general problem mainly regarding mechanical surface loading, again the bonding between coating and substrate has been recognized as R&D-theme.

### 5.1.7 Functional materials

Out of the large variety of functional materials some have been selected by the interview partners as predominant for R&D. These are:

- Semiconductors in general
- High temperature superconductor materials, including subsequent processing routes for engineering applications
- Magnetic materials which are prone to further miniaturization
- Catalytic materials for fuel cells; e.g. substitution of platinum
- Materials which overcome difficulties by extreme nonlinear friction - including slip-stick effects - in several servo-controlling processes as for driving components and roboters.

### 5.1.8 Raw materials and recycling

In the field of raw materials, different opinions are to be recognized: Whereas in the "Southern EC countries" the interest is mainly in mining technologies and their application, the "Northern EC countries" put more emphasis on improvements in remote sensing techniques, the optimization of refining techniques and the minimization of pollution (development of "closed-loop" technologies). Because of the importance of raw materials - as initial technological step in the product cycle - R&D in this field should be included in future community activities. Besides "primary raw materials" also "secondary raw materials" in connection with approaches to recycling and reuse should be considered.

## 5.2 Technical area 2: Design

With respect to modern design procedures various R&D suggestions have been put forward by the interview partners. These go far beyond the few well-known conventional criteria such as:

- Function of the component or structure,
- Stress and strain distribution; strength and endurance,
- Manufacturing and assembly,
- Costs.

To meet future requirements new ideas must be implemented into the design concept. So additional criteria have to be developed e.g. for computer aided concepts (CAD) and/or expert systems. This is not only a technical but a didactic task too and can be performed only if beforehand the respective human, social and environmental problems have sufficiently been perceived.

It is agreed in general that already from the beginning of the design one has to take into consideration the specific material performance. This includes not only the properties (E-modulus at different temperature, strength, fatigue, formability data, crash models etc.) but other matters such as availability, manufacturing, costs and recycling too. Implemented data bank systems are of benefit and probably not to drop in future. Of similar importance is the access to information systems and centers.

As examples for material-specific design, components made of extreme brittle materials (ceramics; problems of strength hypothesis, effect of upsizing and machining) and of structures consisting of shape memory metals (sensor integrated actuator) should be mentioned. A special design methodology has to be developed for composites, especially for long fibre composites. In this case strength and the respective manufacturing routes have to be considered.

Computer aided stress and strain analysis should be implemented into design systems, and for further optimization quick feedback is necessary to predict fatigue, endurance and reliability of the structure.

Design with respect to sufficient safety of the component or structure has to be supplemented by "fail-safe; safe-fail" concepts. A stringent development of these concepts results in more economical design which should save costs and material resources. Further design criteria are power saving manufacturing routes, easy inspection, easy maintenance and repairability during the service time of the structure and easy defunctioning as prerequisite for proper and economical recycling. Recycling of the used materials is the minimum future requirement irrespective of difficulties with some materials as polymer-sets and polymer composites. High value recycling of total components for re-use in new structures is of much greater economical benefit, but it has to be considered already at the components design.

Having in mind all the above mentioned criteria, future oriented design procedures have to consider the total life of the component or structure up to the re-use of the material or removal.

The general trend in design procedure is the increasing application of computers; the capacities of computers and the base design software should be improved including the user shell. On the other hand some software specialization will be of advantage. In general CAD has to be developed far beyond the geometry-oriented technique towards the above mentioned comprehensive procedure. Besides the computer aided stress and strain analysis, a comprehensive software should include computer simulation of necessary manufacturing routes (e.g. deep drawing, bulging, etc.), access to numerical controlled (NC) machining of the components, crash performance (if necessary) as well as thermal and vibration behaviour of the components.

In some fields further developments of design techniques are interdisciplinary tasks: "Mechatronics" and "Optomatronics". Especially the rapid proceeding miniaturization of components, e.g. in the field of electronics results in new problems with respect to high local loading and low velocities of mechanical components resulting in high friction and wear. Sometimes there exist extreme requirements with respect to geometrical or surface accuracy. Some of these problems may be overcome by choosing alternative materials and/or by an "intelligent" design.

Another problem still unsolved seems to be the early availability of design relevant regulations and standards in which the "state of the art" is regarded as quick as possible. Sometimes

standards are over-conservative (e.g. high strength steel grades in civil engineering) and hinder the economical benefits of the technical developments.

## 5.3 Technical area 3: Manufacturing

Manufacturing and processing are in general the most important influences on microstructure, homogeneity and defect distribution and therefore decisive for the properties, performance and quality of materials, components and structures.

### 5.3.1 Continuous and near net shape techniques

Continuous manufacturing routes in general are of benefit not only with respect to costs. They are more prone to on-line processing control and thereby a better quality may be expected. Very often these routes are saving materials and energy too. Out of the variety of this type of processing, continuous casting of steel materials has been suggested as one of the themes for further R&D. One of the goals is to open this manufacturing route for difficult castable steel grades too. Another one is the casting of strips of e.g. 5mm thickness only as basis for a subsequent rolling of thin sheet materials (near net shape manufacturing). Some manufacturing procedures are developing to a higher degree of integration of different steps. As an example, the integrated steel production is mentioned, i.e. the combination of ore reduction, refining and melting to one process by oxygene and coal injection.

For mass production there exists a strong competition between forging and casting. With respect to forged structural steel components castings of iron with nodular graphite are the alternative. For low density alloys (Al) cheaper casting dominate. Only for high performance requirements forged components are still preferred. An example is the isothermal forging at gradually increasing pressure of turbine disks. This technique results in outstanding good properties.

Precision casting - a near net shape technique - is one of the manufacturing routes of increasing importance and a technique with use of permanent moulds too. Another topic for development will be the method of compound (different materials) casting. An interesting combined technique is rheo-casting, squeeze casting. Deformations up to high levels can be applied after casting at temperatures in the liquid-solid-range.

Another near net shape manufacturing is the powder metallurgy (PM) route. Applying extreme fine powders and injection moulding, high performance mass commodity fabrication at reasonable costs is possible, irrespective of the special properties of the material. Special alloys may be produced which are difficult - or even impossible - to handle by melting techniques. The general goal is to arrive at a maximum relative density of the material. Powder metallurgy is used with benefit even for high performance components e.g. turbine disks (jet engines). This demonstrates the high-tech capacity of PM manufacturing routes which is still open for further upgrading by R&D.

A third processing route is a combination of a rough "master manufacturing", e.g. by casting with final fine machining. Conventional machining for mass productions of steel components is based on good machinability of the material. A lot of additives has been tested with non-impressing success; the best results still have been obtained for sulfurized steels.

### 5.3.2 Special manufacturing techniques

Some alternative manufacturing systems mainly for cutting processes are: Laser cutting, for high accuracy; wire based erosion and water jet cutting. Erosion and laser based methods are used for surface manufacturing too. An "intelligent" manufacturing combination is under discussion with respect to machining ceramics in the plastic condition: The material is laser beam heated immediately at the tool.

There is a large demand for R&D with respect to these alternative manufacturing methods for quite different materials. Besides aspects of costs and ability for mass production the influence of the manufacturing on the performance of the material - e.g. the strength of ceramics after grinding - and other effects have to be recognized, such as noise and vibration.

Out of the large variety of very special manufacturing systems some have been mentioned which could be of general interest for R&D activities:

For the manufacturing of fibre reinforced polymers a prediction of the fibre orientation is required. For long fibre composites numerical controlled (NC) winding techniques are an aim for R&D to arrive at optimized components with respect to stress and strain distribution and weight. Under discussion are glass matrix composites; for this material quite different manufacturing routes are discussed as casting, sintering and other techniques.

With respect to mass commodity manufacturing of polymer materials injection moulding processes should be improved in order to arrive at optimized temperature control and an improved accuracy. Other problems with respect to mass fabrication are those by higher temperatures of the polymer material and the higher process velocities. Higher temperatures result in decreasing accuracy of the components by shrinkage, higher velocities in dynamic effects, exciting of vibrations and less precision.

Many manufacturing problems in the engineering ceramic industries are still open for further R&D activities; very often the production technology is the limiting factor for the application of special materials. Again the development of continuous processing for difficult ceramic components and materials is an urgent problem. Referring here- to, hot isostatic pressing (HIP) - often necessary for high-tech performance - is a special problem. On the other hand injection moulding complies with these requirements, but the binding agent portion should be less than 25 % for high performance ceramics. Especially for ceramic matrix composites - short ceramic fibres - a large demand for R&D is mentioned with respect to the manufacturing routes. The aim is to arrive at an optimal alignment of the fibres and so at high stress and improved toughness.

### 5.3.3 Joining and assembly

A considerable amount of details was given in the discussions with the experts regarding problems of joining materials and components. Important with respect to economical effects are those methods which can be less influenced, such as glueing, soldering, diffusion welding, pressure welding and friction welding. Narrow gap welding and under water welding need further R&D activities. A similar demand exists for the fields of sensor controlled welding, laser welding and in-line non-destructive testing of spot welds. Various unsolved problems are related to mutual joining of ceramic materials and joining ceramic materials with metals.

Especially for high temperature application (800 to 1200 °C) e.g. for heat exchangers the performance of the joining techniques are the limiting factors. For polymer materials the state of the art at ambient temperature has been sufficiently developed; but there are still demands for a standardization of the techniques. With respect to adhesives for different materials there is an urgent demand for specification to improve the acceptance of glueing in general as integral part of overall design and manufacturing.

#### 5.3.4 General aspects of manufacturing

One of the basic impression is that manufacturing is often the main hindrance for the introduction of new materials. If technical details for manufacturing in principle are available, the aim for further development is to transfer these details to fabrication routes suitable for mass production. Low energy consumption, if possible no environmental impact and a high quality standard are vital prerequisites. Of course, recycling and reasonable disposal of waste material and auxiliary agents has to be recognized. For the last time reasonable disposal became more important than saving of material resources.

Mass production finishing plants very often do not have an own quality control for incoming base material but refer to the quality control system of the suppliers. Besides a proper quality documentation, advanced methods of on-line testing and in-line controlling of the manufacturing process are more and more important for high quality performance. This results in a demand for R&D in the field of simple and robust on-line NDT sensor technology e.g. X-ray, tomography and ultrasonics. Flexible computer-aided manufacturing (CIM) is based on sensor aided control; it is of increasing importance and leads to high economical competitiveness.

An accelerated development appears to be necessary with respect to robotized manufacturing lines in Europe. Numerical controlled spot-welding roboters are already integrated into manufacturing lines; but necessary are robotized assembly lines with improved gripping devices, sensors and advanced computer aided vision systems and image analysis.

For mass commodity manufacturing of complex structures a small vertical extent is of economical advantage: Quick and flexible changes of the manufacturing programmes are possible but a reliable supply "just in time" is a necessary prerequisite. This is not only a technical but an organizational task too.

### 5.4 Technical area 4: Testing and assessment

A key aim of future industrial testing and assessment techniques is to improve quality of products at high throughput of a manufacturing line. These techniques demand the in-situ-control of important process parameters such as temperatures, dimensions, velocities etc. which are fed back to control the manufacturing process. For this purpose suitable sensors have to be developed. In this field there is need for new sensor materials, whereas the electronic side is well developed. Other problems are the contamination of sensor materials and sensors for fluid measurements.

Similar problems are existing with respect to sensor technique applicable for the testing and demonstration phase of engines and total plants.

### 5.4.1 Non-destructive testing techniques (NDT)

Further demand for R&D activities is recognized in the field of non-destructive control of components, e.g. by ultrasonics, eddy current, acoustic emission and holography techniques. Quality control of semi-finished materials such as rolled strips, continuous cast slabs and deep drawn components can be performed by image processing if the technique is developed up to a sufficient resolution. A similar procedure is the radiography of components and assemblies by X-ray imaging and computer tomography.

An intelligent procedure prone to further R&D is an assessment of damage and deterioration of fibre reinforced composites by application of optical fibres as sensor elements. In this case structural (load carrying) properties are combined with functional (NDT) ones.

Besides these general testing procedures - also partially related to the manufacturing routes - many details with respect to specific testing procedures have been mentioned by the interview partners. For many of these procedures there is a lot of demand for further improvement and some new test strategies should be developed.

The non-destructive test (NDT) methods are still under discussion mainly with respect to the detection of defects in the range 50 to 20  $\mu\text{m}$ ; each method will be accepted if a detection is guaranteed. Other problems - still unsolved - are an early detection of small failures (fatigue cracks etc) or of a material deterioration (creep) a long time before total damage; this is important for an assessment of the residual service endurance of a component. Techniques for the NDT-inspection of components and total systems - e.g. instead of proof testing - are welcome too. Another problem is e.g. the inspection of the remaining prestressing of bolt connections without an influence of friction.

### 5.4.2 General aspects of testing

The following test procedures have been mentioned as open for further R&D:

- Procedure of testing at high and low temperatures including full scale tests
- Determination of the mechanical behaviour in specific environments, corrosion tests
- Assessment of long life behaviour of materials and components on the base of short time tests.

A significant interest is obvious for an improved assessment of the formability performance of material used for respective manufacturing routes. The evaluation of flow curves of sheet materials up to very large deformations (including the necking of tensile specimens) as well as considerations with respect to transferable failure criteria applicable to different forming procedures are of great interest.

A class of material of still insufficient testing procedures is engineering ceramics incl. ceramic matrix composites. The usual bending test is not sufficient for a thorough classification of the material and for a reliable transfer of specimens characteristics to components. Therefore it is unanimously agreed that more R&D activities are necessary to improve testing techniques including testing of ceramic components considering respective constitutive equations, failure hypothesis and deterioration set-up.

In addition to the above-mentioned details problems are discussed with respect to tribological testing (specimen, components), electrical contacts and surfaces. Of special interest is the friction and wear performance of simple matings in the mass commodity manufacturing for which test procedures are necessary.

A general problem important for many fields of testing is the question how extensive laboratory results are representative for the performance of components and structures under service conditions. The transfer route includes the effects of up-sizing, manufacturing, environmental influences etc. With a view to this point there is a demand for an improvement of test strategies for real components.

In general there is some need to arrive at a quicker transfer of testing techniques developed in an academic frame to shop floor application in the industry. Supposed an agreement on testing procedures within a limited group of interest (e.g. national; supplier - customer) the details and framework should be at once consistent with internationally acceptable procedures for standardization.



## 6. Conclusions

Based on the analyses of the state and trends in industrial and materials technologies, as well as on the results of the enquiry by questionnaire and the consultations with experts, the following conclusions for future R&D in the fields of industrial and materials technologies in the EC can be made:

### Technical area 1 (TA 1): Materials Technologies

Materials constitute the physical matter of all industrial products; they are thus a key factor in technological and economic developments. Materials research and engineering must be related to the "total product cycle" in the various industrial sectors: from raw materials processing via materials development, component design and manufacturing to product performance and, finally, to deposition or preferably recycling. Future materials R&D efforts should apply a "two-sided strategy" considering:

- (i) "Advanced materials" for high-tech applications, where new developments or radical innovations may also have important "spin-off effects" for commercial applications,
- (ii) "Engineering materials" for mass commodity applications, where already incremental progress in materials properties in combination with improved manufacturing techniques can lead to considerable effects.

#### TA 1.1 Raw materials and recycling

##### 1.1.1 Exploration

Priority goals:

- (a) Improvement of remote sensing techniques; e.g. application of advanced electromagnetic, radiometric and spectrometric techniques or possibly lasers; increase of sensing penetration depth
- (b) Improved mining technologies, e.g. drilling techniques for cost effective exploration
- (c) Modelling the exploration of mineral deposits
- (d) Exploration of complex resources containing basic and strategic metals
- (e) Advanced exploration techniques with improved safety and environmental conditions

##### 1.1.2 Exploitation and processing

Priority goals:

- (a) Development of "clean" raw materials processing techniques, i.e. "closed loop" technologies and environment protective processes, e.g. substitution of pyrometallurgy by hydrometallurgy
- (b) Improvement of geochemical analytical tools: smaller samples, multicomponent analyses, inexpensive methods
- (c) Advanced processing techniques for high purity metals and industrial minerals

- (d) Bio-chemical processing, mining and quarrying technologies
- (e) Development of techniques for obtaining minor constituents as by-products in exploitation processes

### 1.1.3 Recycling

Priority goals:

- (a) Physical and/or chemical separation of multimaterial products
- (b) Exploitation techniques for residues, particularly waste and scrap
- (c) Processing of complex residues by thermal, hydrometallurgical and refining techniques
- (d) Development of recycling techniques for advanced and engineering materials, like polymers or composites

## TA 1.2 Advanced materials

Emphases should be on innovations in composites, ceramics, alloys and polymers, concentrating on relations between processing, properties, performance and price. In this context, microstructure research - including development and application of appropriate test methods - is an important prerequisite for understanding variations of materials properties by variations of composition, processing routes and treatment. This applies to all classes of materials. The following priority (horizontal) goals are of general importance:

- (i) Development of materials with special microstructures, e.g. "nanocrystalline" and amorphous materials, study of structure-property relations
- (ii) Atomic scale studies of materials surfaces and materials structures (e.g. application of scanning tunneling microscope) as basis for quality assessment and further developments of microelectronics and micro-mechanics components
- (iii) Microstructural studies concerning the deterioration of materials, e.g. the initiation mechanisms of cracks in the micron and sub-micron regime
- (iv) Interface research, e.g. with respect to the mechanisms of adhesion, debonding and delamination of composites, sandwich structures and coated materials.

### 1.2.1 Composites

Priority goals for composites with different matrices:

- (a) Polymer matrix composites with improved thermal performance, increased stiffness and low density, high strength and fracture toughness, improved resistance against aggressive agents
- (b) Metal matrix composites (e.g. Al-matrix with ceramic fibres) with a combination of high strength, stiffness and good corrosion resistance
- (c) Ceramic matrix composites with improved resistance against thermal and chemical attack, upgrading with respect to strength, fracture toughness and damage tolerances
- (d) Development of technologies needed to address problems associated with large scale production of composite materials

### 1.2.2 Ceramics

Priority goals for monolithic engineering ceramics:

- (a) Improvement of the reliability of ceramic structures through intensified R&D activities in the fields of powders and agglomerates ( $< 1 \mu\text{m}$ ), e.g. for non-oxide ceramics (SiC, Si<sub>3</sub>N<sub>4</sub>, B<sub>4</sub>C, BN)
- (b) Upgrading of structural ceramics with respect to brittleness, thermal shock resistance, fatigue strength, creep resistance and resistance against chemical attack
- (c) Research for toughening mechanism for advanced structural ceramics, e.g. crack-arresting mechanisms
- (d) Development of functional ceramics with special electrical, magnetic and optical properties or with specific sensor functions

### 1.2.3 Metallic alloys

Priority goals:

- (a) Upgrading of materials for high complex mechanical and environmental (thermal and corrosive) attack, e.g. superalloys of the polycrystalline, directionally solidified and single crystal type as well as intermetallics and mechanically alloyed materials (e.g. oxide disperse strengthened, OSD)
- (b) Upgrading of low-density materials, e.g. Al- and Ti-alloys and Al-Li-alloys with improved strength and stiffness
- (c) Improvement of engineering metallic materials with respect to economical effects and competitiveness, e.g. micro-alloyed steels, cast metallic materials (e.g. austempered nodular cast iron) by advanced routes and easy recycling, duplex-structure stainless steel, materials and structures via powder metallurgy routes

### 1.2.4 Polymers

Priority goals:

- (a) Polymers and polymer blends with improved thermal properties for structural applications, e.g. flow (creep) resistance at elevated temperatures, hydrothermal stability, thermal conductivity, fire resistance without use of halogen elements
- (b) Functional polymers with special (non-linear) optical properties for future applications in photonic systems
- (c) Functional polymers with special electrical properties, e.g. electrical conductivity (reversible switch on/off) as well as low charging
- (d) Polymer biomaterials with suitable mechanical properties, no degradation inside the body and no release of toxic monomers
- (e) Improved (thermoplastic) polymer processing technologies for reliable components at low costs; research to better understand the relationships between processing, structure, morphology and properties

## TA 1.3 Optimization of materials properties for performance

Developments in materials (composites, ceramics, alloys, polymers) should lead to better structural and functional properties. The following engineering materials properties appear to be of basic importance for the functioning, performance and competitiveness of industrial products. These properties (or combination of them) must often be "tailored" to specific application requirements.

### 1.3.1 High temperature/strength

There is an increasing need for "high temperature materials" in power generation, energy conversion, and automotive industries for more efficient high temperature combustion with minimum combustion products pollution. Potential suitable materials are metallic superalloys, intermetallics, monolithic, reinforced and toughened ceramics; high temperature coatings; high temperature insulating materials (low density, low thermal conductivity); refractories and carbon/carbon composites. R&D goals should aim at

- Better long term stability in service
- Increased strength, fatigue resistance and toughness
- Better creep resistance
- Better thermal shock resistance
- Better performance repeatability and reliability
- Low manufacturing costs

### 1.3.2 Light/strong

Light weight, high strength/stiffness materials are required to sustain the loads and conditions created in moving machinery, robotics, structures and engines used in transportation and in the aerospace industry. Potential suitable materials are polymeric systems, Al-, Mg- and Ti-alloys and composites. R&D goals should aim at:

- Better understanding of materials behaviour under complex loading, fatigue conditions
- Development of modeling and design techniques
- Better specific stiffness
- Improved threshold for higher temperature applications and hot/wet conditions
- Better durability and environmental resistance
- Lower manufacturing costs

### 1.3.3 Electronic/magnetic/optical

There is an increasing need for materials with specific functional properties suitable for further developments and innovations in information technologies, including magnetic recording media and photonic systems. Due to a very large spectrum of materials properties needed in this field, a selection has to be done, considering either the strategic interest or present strong position of EC-countries, expected development of the market in future, taking into account industrial as well as academic expertise. Selective R&D goals may aim at:

- Improved electronic properties of (large) semiconductor components (Si, GaAs, InP, CdTe and related alloys) and epitaxy of these materials, including energy assisted techniques (ions, photons)

- Better functional ceramic materials properties, concerning insulating ceramics (chip carriers, piezo ceramics), new sensors, optoelectronic ceramics ( $\text{LiNbO}_3$ ), superconductors as films and wires, high  $T_c$  materials.
- Advancing magnetic materials properties for high density data storage (new ferrites, hexafluorides, magneto-optical thin films) as well as a possibly further improved performance of soft and hard magnets
- Improved optical properties of glasses and polymers through increased purity of existing materials, new materials in ultra far infrared, crystalline fibres, polymers for non-linear optics

#### 1.3.4 Building/Civil engineering

There is a strong need to upgrade in this area the research level, the building technologies, and the prediction and performance of properties and behaviour. Besides the application of better construction methods and management techniques, failure detection and diagnosis (non-destructive techniques), maintenance, repair and restoration, improved materials may be applied. The relevant materials areas include metallic materials (reinforcements for concrete: rods, wires and fibres), glasses and ceramics (structural, sheltering, facing and light transmission function, reinforcing fibres), concrete and minerals (granulated textured composites), organic materials (polymers, bitumes), cellulose, wood and derivatives. R&D activities must concern:

- Construction materials and components, e.g. better reinforcement (improved strength, lower cost, better bonding) of concrete, cement and plaster; better binders for granulated structures (bonded aggregates, hydraulic and bituminous concrete); development of light weight structures (synthetic wood); modeling of the behaviour of materials and structures; repair techniques
- Maintainability and durability with respect to performance of structures, shelter and weather functions, resistance to corrosion and ageing, wearing courses on roads, protection of wood against fungi and insects; application of improved reconstruction techniques
- Building services, i.e. improved thermal and acoustic insulation, light transmission through controlled thermic and light functions (electrochromic glass, valve systems) as well as increased acoustic damping properties of building materials
- Safety through improved fire resistance (combustibility, flame propagation), improved reliability of structures in risk areas, improved crack resistance of concrete structures against shock waves and impact, new approaches to limit the risk of release of smoke, pollutants and toxic gases from foams, plywoods, chipboards, etc. (e.g. formaldehyde, freons)
- Automation of production through application of computer-aided design (CAD) and robotics; costs reduction

#### 1.3.5 Quality and reliability through deterioration research

The functional capability, reliability and safety of industrial products can be greatly influenced detrimentally by materials deterioration processes. Depending on the industrial application and performance requirements, deterioration processes which act primarily at material

surfaces, and processes which lead to the failure of bulk materials and structures must be considered. The malfunction and failure of industrial products due to these deterioration processes still lead to economic losses of up to 3 to 4 % of the gross national product of EC member states i.e. some ten billion ECU. Intensified research on these problems will benefit all industrial branches with the aim of assuring their quality and function, thus improving competitiveness. R&D activities must be addressed to the basic failure mechanisms and combinations of deterioration processes related to

- fracture
- fatigue
- corrosion
- tribology and wear.

## Technical area 2 (TA 2): Design

The design, i.e. the systematic planning and developing of products for the market is one of the most important tasks of industrial engineering. For the product development and the presentation to the customer, the degree of novelty of the product is fundamental. For future industrial products, the further development of a total design concept is an important task. This should cover the following aspects: function, economic feasibility, safety and reliability, production, quality control and product assurance, assembly, transport, performance, maintenance, recycling, expenditure and costs. The following aspects appear to be of fundamental importance for future R&D strategies in this field:

- (i) Consideration of the total life of components and structures, including defuncting, decommissioning and recycling
- (ii) Design with respect to manufacturing routes, mainly energy and materials saving processes
- (iii) Design with respect to damage tolerance, maintenance, supervision and quality management.

### TA 2.1 Design concepts for industrial products

Priority goals:

- (a) Transfer of materials properties from specimens to components and structures; influence of geometry, down-sizing and up-sizing
- (b) Special design of components made out of short-fibre and long-fibre reinforced composites
- (c) Design of compound components, especially polymers combined with other materials; advanced sandwich components and cellular structures with high stiffness
- (d) Design of micro-mechanic components, also made out of polymers
- (e) Design strategies with respect to brittle materials (ceramics); critical points of load introduction
- (f) Probabilistic approach to design, reliability models, distribution functions of materials properties
- (g) Material flow calculation for improved design of processing tools, e.g. metal forming moulds

## TA 2.2 Computer-aided design (CAD) and mathematical modeling

Priority goals:

- (a) Development of CAD-systems integrated with data-bases which should include
  - (i) standards which have an influence on the geometry,
  - (ii) data with respect to geometry and materials of semi-finished products, standard components, and earlier design models,
  - (iii) text and graphic information on guidelines, regulations,
  - (iv) general materials data.
- (b) Improvement of the efficiency of CAD ("beyond the pure geometry-oriented design") as a basis for increased application; better adaptability of CAD systems
- (c) Application of improved mathematical modeling techniques, like finite elements calculation (FEM) for the assessment of strength, life time and safety; use of materials models for deterioration and failure
- (d) Improvement of the application of "expert systems" for design and the assessment of life time and safety

## TA 2.3 Integrated multi-sectoral concepts

Contemporary design strategies must recognize that most industrial products nowadays combine parts or components with complementary structural and functional properties to give complete engineering systems. Thus, concepts for the integrated design of such multicomponent systems are needed.

### 2.3.1 Mechatronics

Mechatronics is the integration of mechanical and electrical/electronic engineering, supported by microcomputing techniques to give systems which have the advantage of combined use of these components and a possible optimization of the function of the whole system. Mechatronic systems, like modern industrial robots, require several R&D efforts aimed at overcoming the traditional boundaries between the major engineering disciplines. Fully integrated project teams must be created including product designers working with manufacturing, purchasing and marketing personnel to design both the product and the manufacturing system.

### 2.3.2 Optomatronics

Optomatronics systems integrate advantageous optical properties of materials together with electronic and micro-computer components. In optomatronic (or photonic) systems information is carried by pulses of light. The light source is a semiconductor laser or a light-emitting diode, and the transmission medium is a hair-thin fibre-guide of silicon glass. In optomatronic systems, information can be transmitted at a rate much higher than the pulse rate of conventional electrical signals. To apply these potential benefits to the information and communication sectors, considerable R&D efforts related to the development of materials and industrial production of components as well as to the design of integrated systems are necessary.

## Technical area 3 (TA 3): Manufacturing

Manufacturing technologies, including shaping, forming, joining, assembly and surface optimization are crucial for achieving quality and efficiency in any technological enterprise. The way in which matter is processed to form bulk materials, components, devices, structures and engineering systems is a major factor in determining the success of efforts in sectors ranging from construction to electronics industries. Depending on industrial sectors and product types, attention must be directed to flexible "small-batch" production technologies as well as to improved "mass-production" technologies, recognizing "just in time concepts", in order to meet an emerging need for identical products in large quantities. For future R&D efforts the following general trends and requirements should be noted:

- (i) Replacement of "batch processes" by integrated techniques and continuous processing, especially improved casting and forging technologies
- (ii) Near net-shape technologies
- (iii) Machining of advanced materials, especially ceramics and composites
- (iv) Efficient joining and assembly techniques, including robotics
- (v) Manufacturing technologies with reduced environmental impact ("closed-loop"); recycling, and low energy consumption
- (vi) Integration of sensors, computers, information and control systems in the production lines and adjustment of work to human, social, economic and environmental factors, eventually leading to "intelligent" manufacturing systems.

### TA 3.1 Manufacturing technologies for industrial products

The optimization of manufacturing technologies for industrial products must be oriented on the type of material to be manufactured or processed. Thus, the following R&D aspects may be considered.

#### (a) Manufacturing of ceramic materials

- Pure powders with narrow particle size distribution
- Sol-gel-techniques
- Organo-metallic processes for powder production
- Wet forming techniques
- Optimized paste for extrusion and for injection moulding
- Economical sintering processes and sinter/hot-isostatic-pressing, HIP-techniques
- Manufacturing routes for components free of internal defects
- Techniques for the production of ceramic matrix composites with long fibres

#### (b) Manufacturing of metals and alloys:

- Die casting and injection die casting
- Continuous casting of thinner flat, bar and wire material combined with rolling; near net shape casting
- Thin walled extrusion
- Rapid forming techniques which result in special properties of metals



### (c) Manufacturing of polymers:

- High speed injection moulding with high accuracy; in this context, the rheology during mould charging is important
- Miniaturization of injection moulding for small electronic structures
- Electrochemical forming and machining; machining and laser cutting
- Manufacturing of very thin structures and multiple layer structures
- Deep drawing and stretch forming of polymers
- Improvement of prepregging techniques; extrusion with prepregs
- Three-dimensional fibre preforming
- Rationalization by combination of chemical reaction and extrusion; reaction injection moulding for thermoplastic material

### TA 3.2 Sensor-aided, computer-and-human-integrated manufacturing (SCHIM)

On-line computational control of process parameters can lead to major improvements in product quality and performance as well as to increased efficiency and reduced costs. Manufacture and materials processing typically involves unusual and sometimes extreme conditions of temperature, pressure, strain rate, flow velocity, or other material or systems parameter. The phenomena that occur during manufacture are generally complex and highly nonlinear. In recent years, some robust nondestructive sensors have already been developed to measure materials properties during processing. The introduction of such sensors earlier in the process stream should enable improved control and rejection of bad products at minimum value-added process steps. Developments in this field will require the combined efforts of experts in sensor developments, materials modeling, taking into consideration the complex relationships between process variables and product structure, and the adjustment of work to the human being.

Priority goals should concern thus:

- (a) Manufacturing sensor technologies: Development of pick-up systems for the in-situ detection of operating parameters and their utilization for on-line control of processing and manufacture
- (b) Process modeling and simulation: High speed computing capabilities coupled with improved theoretical understanding should provide opportunities for improvements in manufacturing technologies

### TA 3.3 Semi-finishing technologies

Efficient technologies for the manufacturing of semifinished components should be further developed. Priority goals should be related to

- (a) Sheets, especially high performance steel sheets with improved properties: thin, strong, with good stamping and corrosion behaviour; easy weldable and paintable
- (b) Fibres, especially long fibres (e.g. carbon, ceramic) with "high-tech" properties but reasonable costs
- (c) Surface coated components with optimized coating/ substrate properties (dynamic loading, corrosion and wear); polymer components directly paintable.

## Technical area 4 (TA 4): Testing and Assessment

Important tasks of measurement and testing, including chemical analyses, are to predict and to improve the way industrial products and engineering systems behave in service. Improved techniques are needed to detect how materials, components and structures respond to stresses caused by service loading, tribo-mechanical contacts, or temperature variations; how they react to hostile, corrosive environments, and how they undergo internal degradation. Some of the crucial issues are strength, reliability, durability, life prediction and life extension. These aspects are relevant not only for the materials that are used in large structures or machines but also for those that form the functional elements in electronic, magnetic, or optical devices. Generally speaking, R&D efforts in the area of measurement and testing have to recognize the following trends and requirements:

- (i) Change from "off-line testing" to "on-line-testing"
- (ii) Need for experimental and computer-aided techniques to support the "total quality management approach"
- (iii) Necessity of improved methods for prediction and assurance of "life-time" of materials, components and structures in service.

### TA 4.1 Industrial metrology

Measurement and testing techniques for predicting performance of industrial products should be based on fundamental investigation of degradation and failure processes, on rational test procedures and on improved nondestructive evaluation technologies to detect deterioration processes or damage in service. For new components, or structures, these techniques should be part of an integrated engineering process involving not only design to meet performance requirements, but also the appropriate modeling of the processing, manufacturing, or fabrication steps necessary to bring industrial products to service. General R&D requirements could be summarized as follows:

- (a) Combined high-resolution techniques for compositional analyses and non-destructive evaluation
- (b) Analytical-experimental techniques for accelerated tests, short-term tests and testing under extreme conditions
- (c) Quality and function oriented test methods for the early detection of deterioration and damage processes and monitoring of service conditions
- (d) Diagnostic tools for long-term performance evaluation with respect to operating life, retaining life and retaining strength
- (e) Improved techniques of computer modeling and computer-aided testing (CAT) of materials and structures under service conditions

### TA 4.2 Non-destructive testing (NDT) and quality control

Priority R&D goals are:

- (a) NDT for the evaluation of the mechanical properties of materials and with respect to the study of structures, e.g. bonding effects of composites and compound structures
- (b) Laser based metrology and control

- (c) Computer aided image processing and improved computer-tomography
- (d) Development of sensors for various physical and chemical properties of materials and components
- (e) Further development of ultrasonic, acoustic, electromagnetic and radiographic NDT techniques with high resolution and efficiency, automatization of testing and computer-aided testing (CAT)

#### **TA 4.3 Performance testing; assurance for products and processes**

Priority R&D goals are:

- (a) Testing under complex stress states and analytical methods for an assessment of residual stresses; testing and modeling of anisotropic behaviour materials
- (b) Scale tests with respect to actual service conditions, short time tests, and long service time performance
- (c) Early detection of damages; remaining service time and detection of deterioration by aging
- (d) Improvement of corrosion and tribology tests, including standardization
- (e) In-situ assessment of the performance of engineering structures, application of sensor-aided machinery condition monitoring techniques

#### **TA 4.4 Standardization**

The great importance of standardization for trade, industry and economy has already initiated various activities to harmonization, regulations and test requirements and had, for example, lead to the formulation of European Standards compiling general criteria for a harmonized operation of testing laboratories (EN 45.000 series). These activities have profound influence on quality management and quality systems and impact on design/ development, production and final inspection.

Future R&D efforts must cover various aspects of standardization requirements: from prenormative research with respect to inspection, testing and certification to integrated quality assurance and their influence on the various development/design/fabrication/performance stages of industrial products. In addition, some general requirements, e.g. with respect to health, safety, environment and consumer protection must also be considered.

\* \* \*

# ANNEX: Programmes and strategies in industrial and materials technologies

## (A) Programmes and strategies in the United States of America

In 1974 the famous and far-reaching COSMAT-Report "Materials and Man's Need" compiled by the Committee on the Survey of Materials Science and Engineering (COSMAT) was published by the National Academy of Sciences (Ref. A1). The importance of materials in industrial technologies was illustrated by the finding that about 1/5 of the US Gross National Product originated from the extracting, refining, processing and forming of materials into finished products and that manufacturing employment related to materials was over 21 percent of the total US employment. By evaluating information from approximately 1000 questionnaires which were sent out in North America to many different institutions dealing with materials from basic resources to finished products, the importance of materials in the following areas of national impact was pointed out:

- Housing and other constructions
- Consumer goods
- Production equipment
- Transportation equipment
- Communications, computers, control
- Energy
- Environmental quality
- Health service

As early as 1960 a programme to establish "Materials Research Laboratories (MRL)" was launched and supported by the Governmental Advanced Research Projects Agency (ARPA) (Ref. A2). The purpose was to "establish an interdisciplinary materials research program and to furnish the necessary personnel and facilities for the conduction of research in the science of materials with the objective of furthering the understanding of the factors which influence the properties of materials and the fundamental relationships which exist between composition and structure and the behaviour of materials". Within the frame of this program, 12 Materials Research Laboratories were founded till 1969. In that same year, with an annual funding of US\$ 18.97 million, a total of nearly 600 faculty members and 2385 graduate students participated in the program, 360 doctoral degrees were awarded, and more than 2000 papers by program participants were published. The investment in the MRL program has been substantial: ARPA contributed US\$ 158 million between 1960 and 1972 and the US National Science Foundation (NSF) contributed US\$ 261 million to the MRL program between 1972 and 1985.

The important role of materials for industrial technologies was outlined again by the US National Academy of Sciences in 1979 (Ref. A3). The following materials and materials-related developments should have a major impact to society out to the turn of the century:

- High-performance resin- and metal-matrix composites
- Silicon nitride and silicon carbide ceramics
- Rapidly-solidified superalloys
- Single-crystal engine components (e.g. turbine blades)
- Synthetic polymers
- Fibre-optic transmission
- Very-large-scale, integrated-circuit silicon chips
- Bubble memories for computers
- Semiconductor infrared detectors
- Powder metallurgy consolidation techniques
- Precision casting
- Laser treatment of surfaces
- Computer-aided design and manufacturing.

The development of the turnover of materials in the US from 1970 to the year 2000 is illustrated in Table A1. It can be seen that in 1990 the turnover of materials is estimated to sum up to 330 billion US\$ (Ref. A4).

Table A1 Turnover of materials in the US, in billions of dollars

Materials	1970	1980	1990	2000
Metals	120 (49%)	132 (46%)	135 (41%)	141 (38%)
Polymers	36 (15%)	53 (19%)	76 (23%)	96 (26%)
Inorganic materials (e.g. ceramics, glass)	38 (16%)	45 (16%)	53 (16%)	63 (17%)
Others (chiefly wood)	49 (20%)	55 (19%)	66 (20%)	70 (19%)
Total	243	285	330	370

In the middle of the 1980's, there started a great concern in the USA on the huge current-account deficit which totalled US\$ 161 billion in 1987. A team of leading scientists, engineers and economists of the Massachusetts Institute of Technology (MIT) analyzed the state of the US industry. They found that growth in productivity, a crucial indicator of industrial performance, has been slower in the past 15 years than it was for at least two decades before and has fallen behind that in several Western European and Asian nations. These analyses were published in 1989 by the MIT in the book "Made in America: Regaining the Productive Edge"; the book describes strategies for industry, labor, government, and education that will lead to a substantial improvement in American industrial performance (Ref. A5).

In 1989 another comprehensive study entitled "Materials Science and Engineering for the 1990's Maintaining Competitiveness in the Age of Materials" was published by the National Research Council (Ref. A6). The study examined the role of materials science and engineering in 8 US industries that collectively employ more than 7 million people and have sales in excess of US\$ 1.4 Trillion, and it summarizes the materials science and engineering needs of

each of those 8 industries - aerospace, automotive, biomaterials, chemical, electronics, energy, metals and telecommunications. The conclusions contained the following important recommendations:

- Materials science and engineering is crucial to the success of industries that are important to the strength of the US economy
- There is considerable overlap in the generic materials problems of the 8 industries studied; solutions to many of these problems lie at the forefront of research in materials science and engineering
- The industry surveys revealed a serious weakness in the US research effort in synthesis and processing of materials. There are opportunities for progress in areas ranging from the basic science of synthesis and processing to materials manufacturing that, if seized, will markedly increase US competitiveness
- An effective national materials science and engineering program requires healthy, balanced, and interactive efforts spanning basic science and technology, all materials classes and the four elements of the field:
  - (i) Properties,
  - (ii) Performance,
  - (iii) Structure and composition, and
  - (iv) Synthesis and processing
- Progress in the four elements of materials science and engineering can be enhanced through increased R&D on and use of advanced instrumentation ranging from the laboratory bench scale to major national user facilities, and through emphasis on computer modeling and analysis of materials phenomena and properties based on the underlying physical and chemical principles.
- Increased emphasis on performance, especially as it is affected by processing is also needed to improve US industrial products for world markets.

## **(B) Programmes and strategies in Japan**

The Japanese Ministry of International Trade and Industry (MITI) had designated for the 1980's the following five areas as "technologies of the future" (Ref.4.1):

- (i) Biotechnology
- (ii) Micro-electronics
- (iii) New types of metals and alloys
- (iv) Ceramics
- (v) Polymers with special properties

Sixty-seven selected firms concentrated jointly on these technologies under the direction of the ministry and with public funding. Direct subsidies of the ten-year programme amounts to almost US\$ 600 million. In Table B1 a breakdown of the main materials related R&D sectors together with the duration of the programmes and the corresponding funding are listed.

Table B1 Japanese Materials Research Programmes (Basic Technology for New Industries, MITI)

R & D area	Duration	R & D budget
New metallic alloys	1981 - 1988	8 · 10 <sup>9</sup> yen
New composites	1981 - 1988	11 · 10 <sup>9</sup> yen
Fine ceramics	1981 - 1990	13 · 10 <sup>9</sup> yen
Polymer membranes	1981 - 1990	10 · 10 <sup>9</sup> yen
High performance polymers	1981 - 1990	6 · 10 <sup>9</sup> yen
Photoactive materials	1985 -	

Without going into details it should be pointed out that the Japanese intended in this R&D programme to develop materials with specific application-oriented property profiles, as illustrated in Figures B1 and B2 for the examples of high performance ceramics and composite materials.

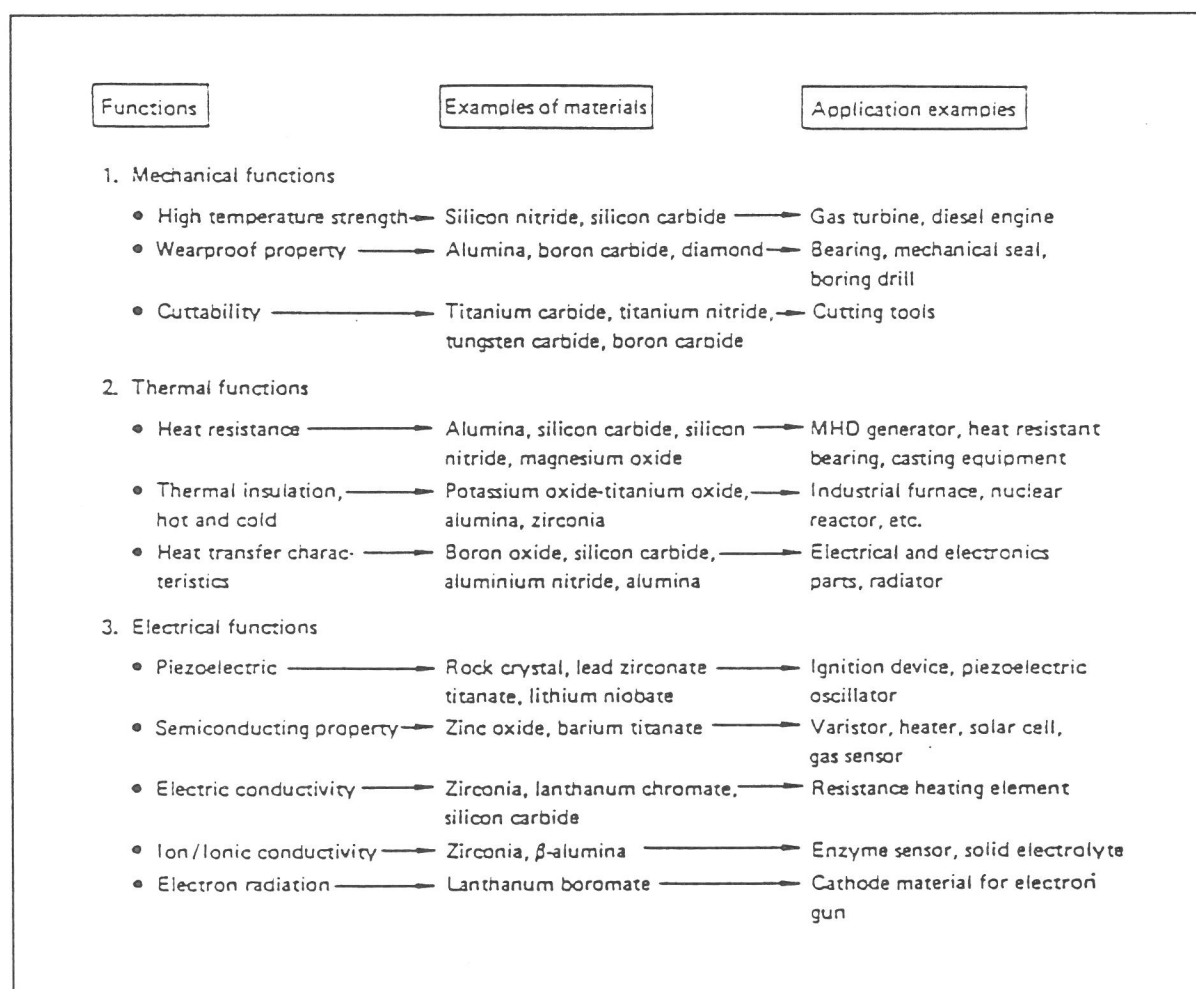


Figure B1 Functions and applications examples for advanced technical ceramic

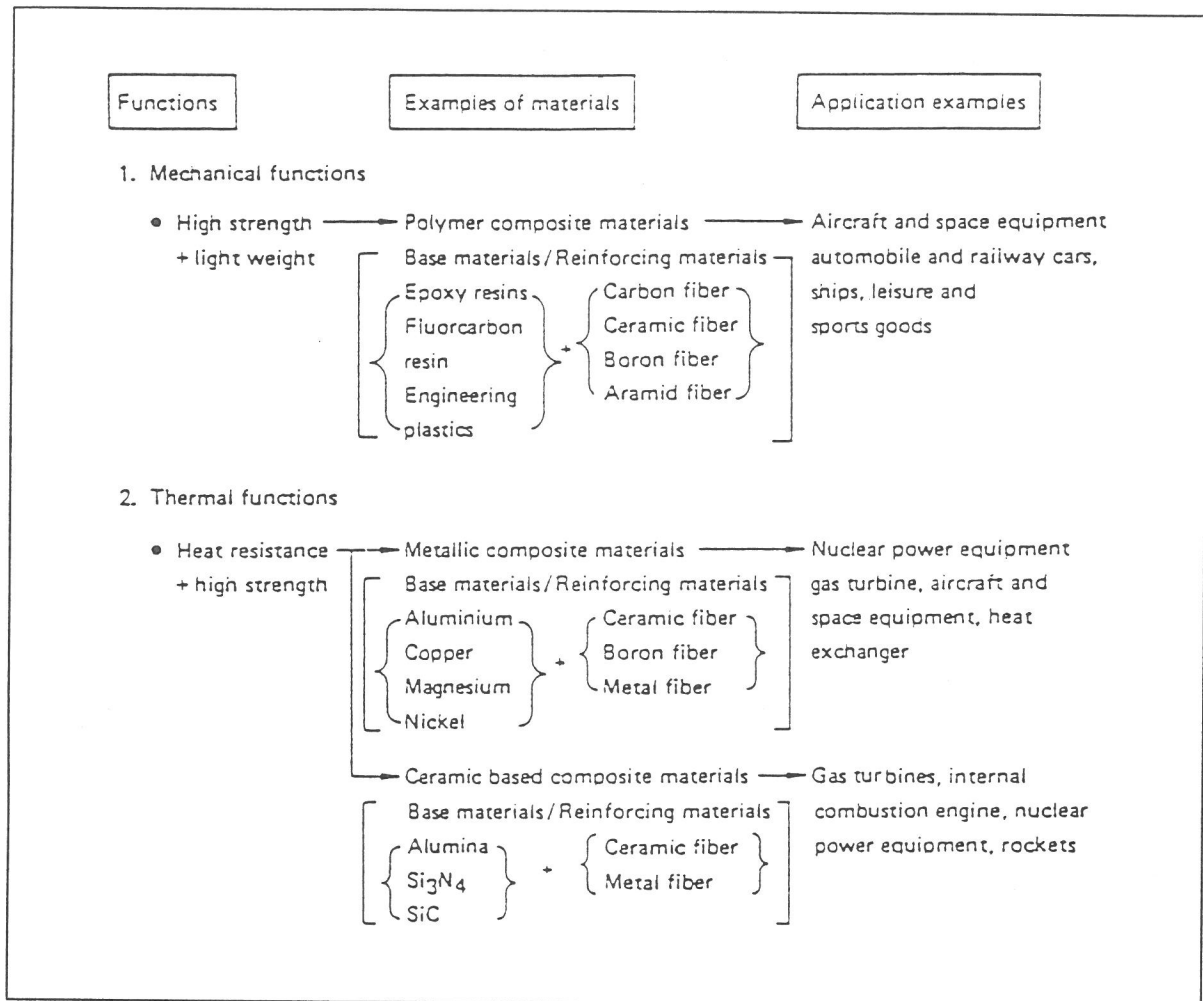


Figure B2 Functions and application examples for composite materials

In 1986 the Japanese External Trade Organization (JETRO) described the main features of the new materials industry as follows (Ref. B1):

- (i) Knowledge and expertise in a variety of technologies is indispensable for the development of new materials. The industry can therefore be said to be knowledge-oriented. In the manufacture of fine ceramics, for example, it is essential to have accumulated information on particle physics, technologies for blending and refining new materials, high-temperature calcination, and wide experience of the production difficulties encountered over long periods of time.
- (ii) In the development and commercial application of new materials, it is often necessary to invest a considerable amount of capital over a long period of time. Therefore, large-scale enterprises or enterprises whose management has clear and firm policies for research and development become the leaders in the modern materials industry.
- (iii) The evolving technology of new materials and their unstable life cycles creates difficulties in assessing the suitability of new materials for specific applications. For example, though boron fibre was developed ahead of carbon fibre and possesses higher tensile strength and elasticity, its commercial application lags behind that of carbon fibre because of higher production costs.



(iv) Because of multiple, small-quantity production, equipment investment for new materials may be small in scale but requires a large labour force.

In 1986 the Japanese Government reviewed its role in the area of science and technology and decided a "General Guideline for Science and Technology Policy", putting stress on the following three items (Ref. B2):

- (i) Promotion of science and technology richer in creativity, strengthening basic research which will lead to next generation technology
- (ii) Evolution of science and technology giving appreciable consideration to the importance of international affairs
- (iii) Harmonization of science and technology with man and society.

Based on this General Guideline, R&D priorities in materials science and technology are put on the following four items:

- (i) Theoretical and systematic elucidation of phenomena at the microscopic level
- (ii) Creation of innovative substance/material by use of extreme environment application of material, of material design techniques, etc.
- (iii) Development of material technology corresponding to society's needs, including reliability technology
- (iv) Development of common/basic technologies such as beam generation, extreme environment generation and analytical/evaluation technologies.

The Japanese R&D efforts are supported by increased activities on the standardization of advanced materials. Figure B3 shows a forecast increase in the number of Japanese Industrial Standards (JIS) on advanced materials as announced in a Report of Standards Department of the Japanese Agency of Industrial Science and Technology (AIST), dated September 1988.

An analysis of the competitiveness of industries in Japan and the European Communities (EC) was published in July 1989 by the Industrial Research Department of the Industrial Bank of Japan (IBJ) with the following main conclusions:

- Construction machinery and machine tools are assessed to be equal in competitiveness in Japanese and EC industries. They enjoy high-level technology as well as quality especially in large-sized machines. Production is increasing in response to growing demand. The ratio of numerically controlled (NC) machines to the total number of machine tools produced is as high as 60 to 70 % in Japan, Germany, UK and France, in comparison with 40 % in the US.
- Automobiles are expanding production with the increase in demand in the EC. Productivity in the EC, however, lags behind that of Japan, and it is judged that competitiveness of the EC, especially of compact cars, is slightly inferior.
- Industrial electronics production in the EC is increasing with the expansion in demand in telecommunications equipment and computers. However, competitiveness in
- Computers in the EC is weaker compared to that of foreign makers, and more than half of large-scale computers installed in Europe are produced by IBM and other American manufacturers.

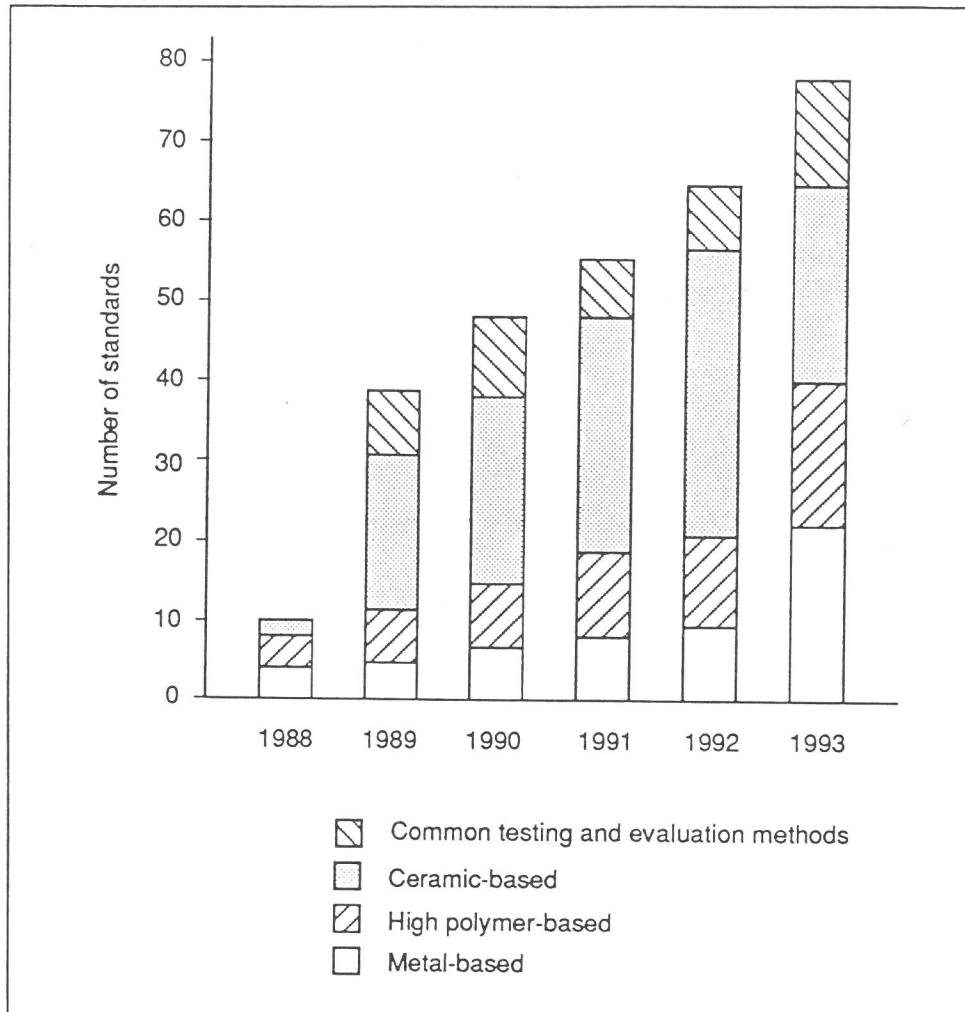


Figure B3 Forecast increase in number of Japanese standards on advanced materials

- Chemicals and pharmaceuticals in the EC enjoy strong competitiveness in comparison with Japanese industries in corporate income as well as in technology. The trade surplus of these industries in the EC has been expanding. Technological superiority is also observed in basic research in the EC.
- Iron and steel industries' competitiveness in Japan is slightly superior to that of its EC counterpart. Also, EC productivity is slightly lower than that of Japan. In 1986, the ratio of steel produced by the continuous casting method to total production was 76 % in the EC and 95 % in Japan, yield was 82 % in the EC and 96 % in Japan, and labor productivity measured in terms of crude steel production was 220 tons per employee in the EC and 367 tons per employee in Japan.

### (C) Programmes and strategies in the European Communities

An overview on main industrial sectors in the EC by output and employment has been already given in Chapter 1 (see Table 1.1). A retrospective comparison between the trade balance in the main industrial sectors of the EC and those of USA and Japan is made in Figures C1 to C13 (Ref. C1). The graphs show the development over a 10-years period in an interpolating presentation ("cubic-spline technique").

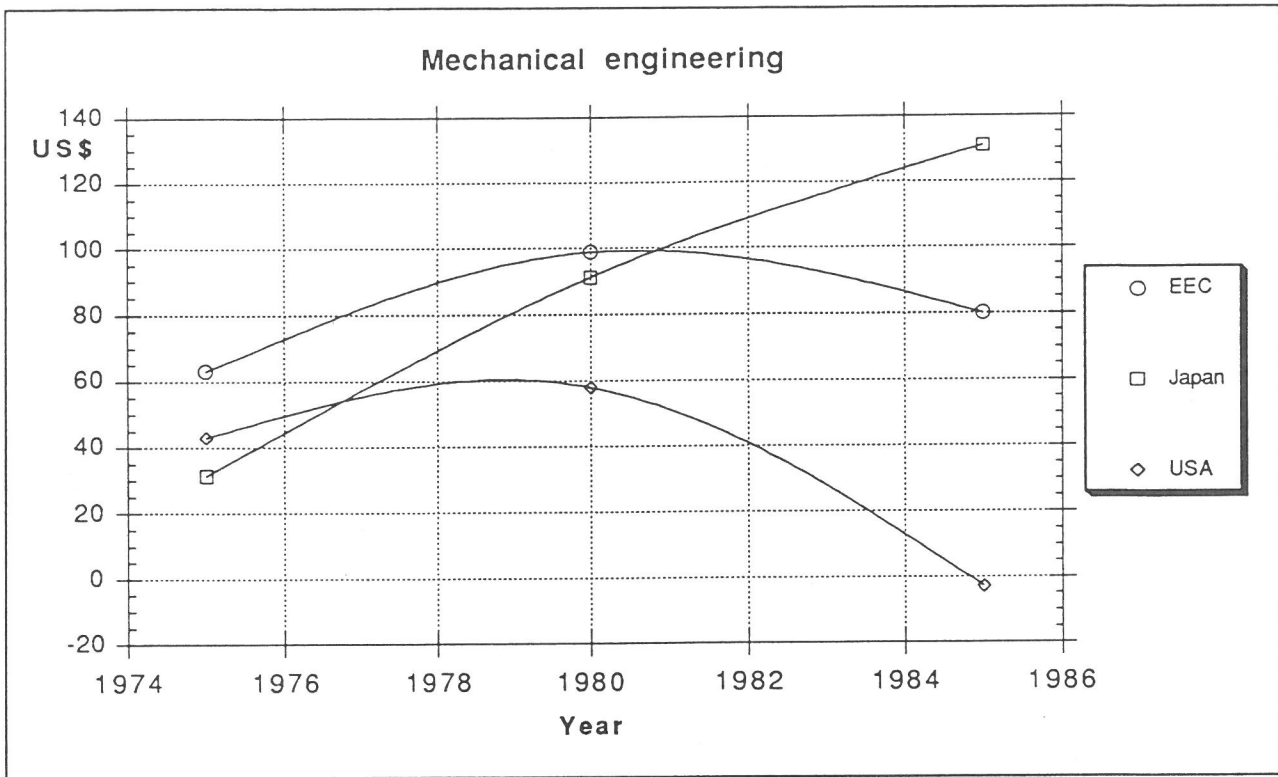


Figure C 1 Trade balance (export minus import per capita at current prices)

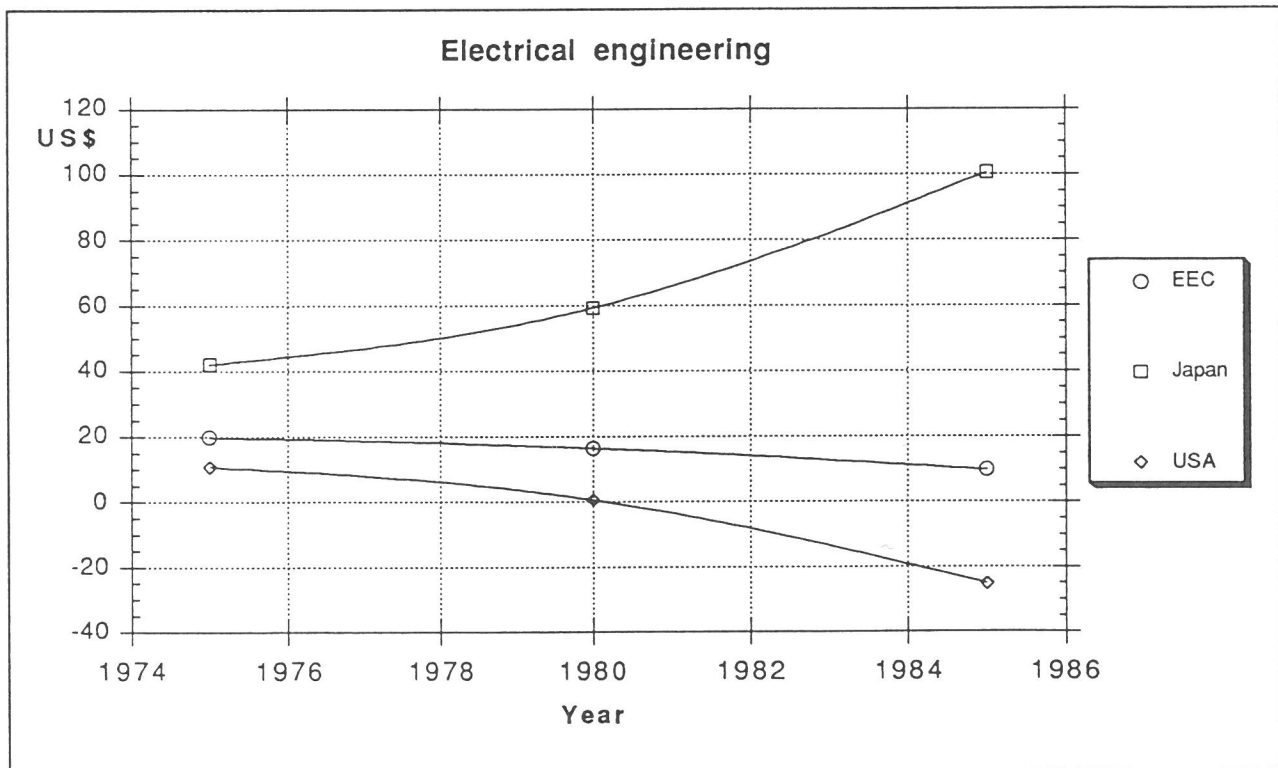


Figure C 2 Trade balance (export minus import per capita at current prices)

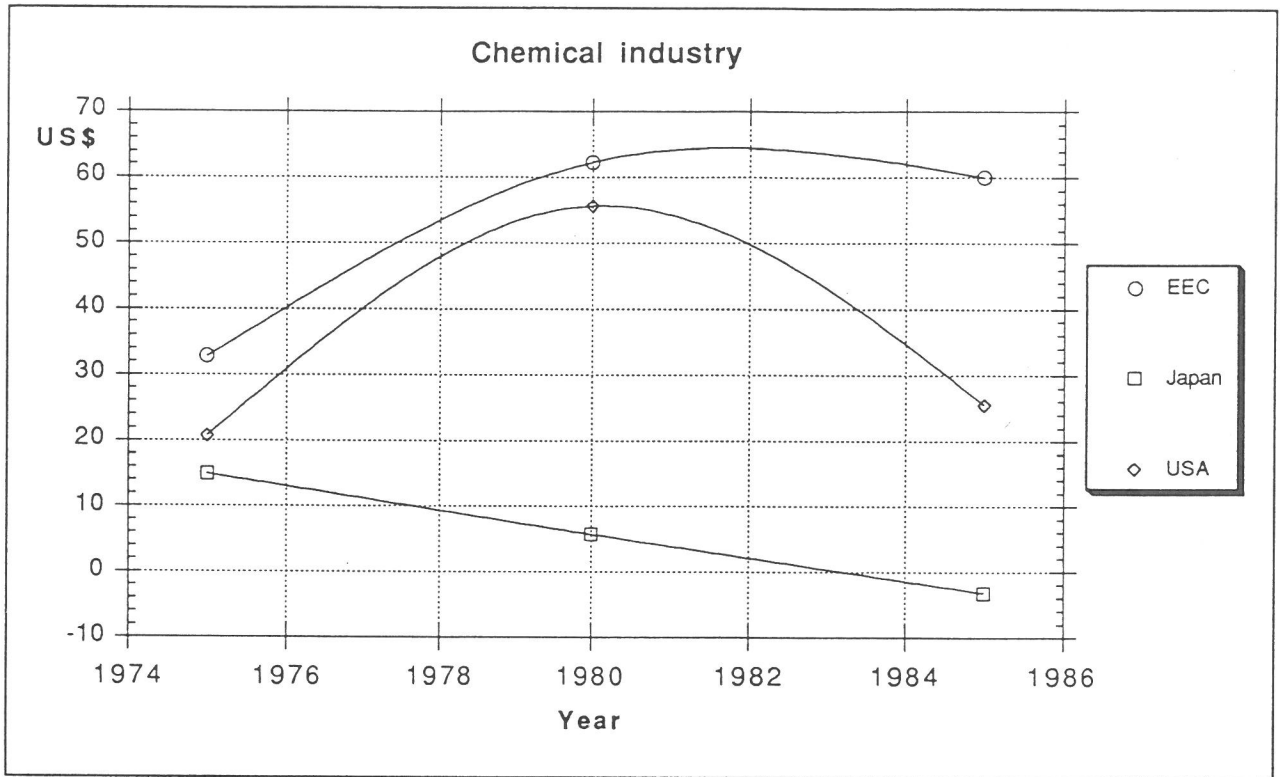


Figure C 3 Trade balance (export minus import per capita at current prices)

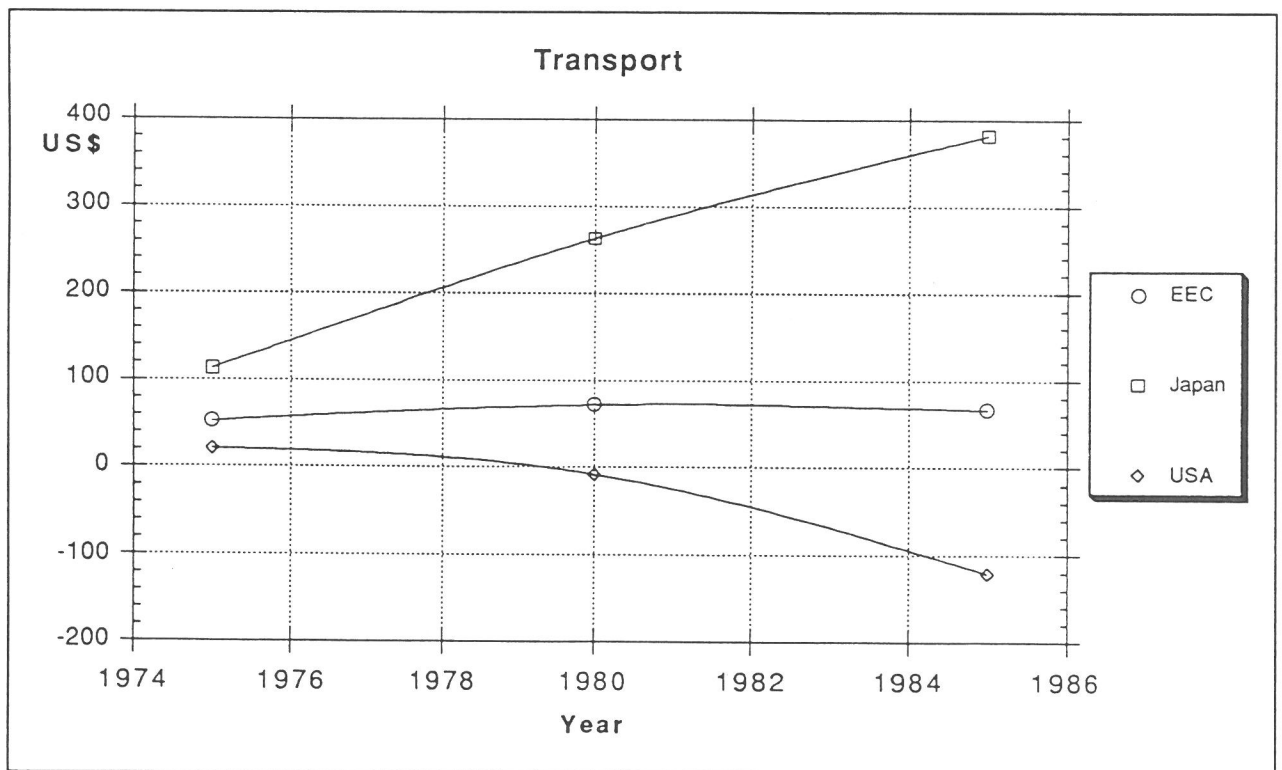


Figure C 4 Trade balance (export minus import per capita at current prices)

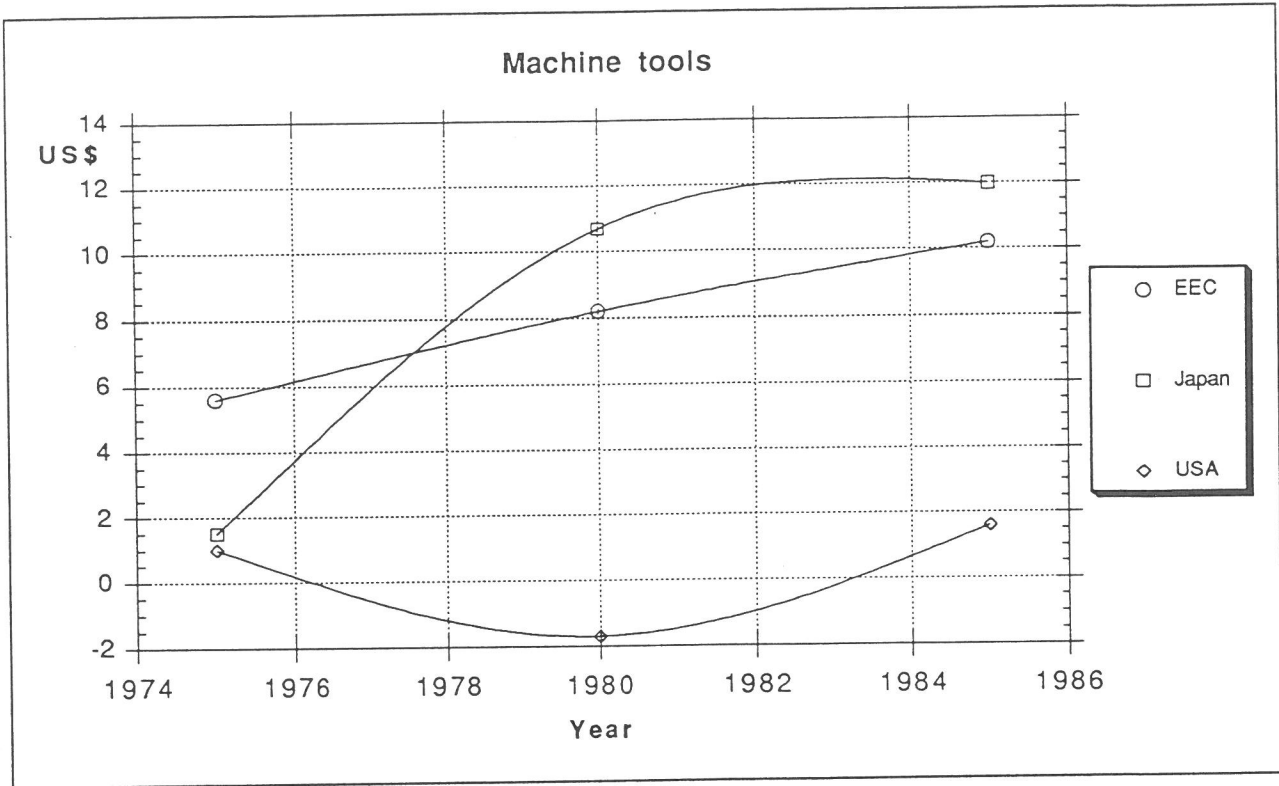


Figure C 5 Trade balance (export minus import per capita at current prices)

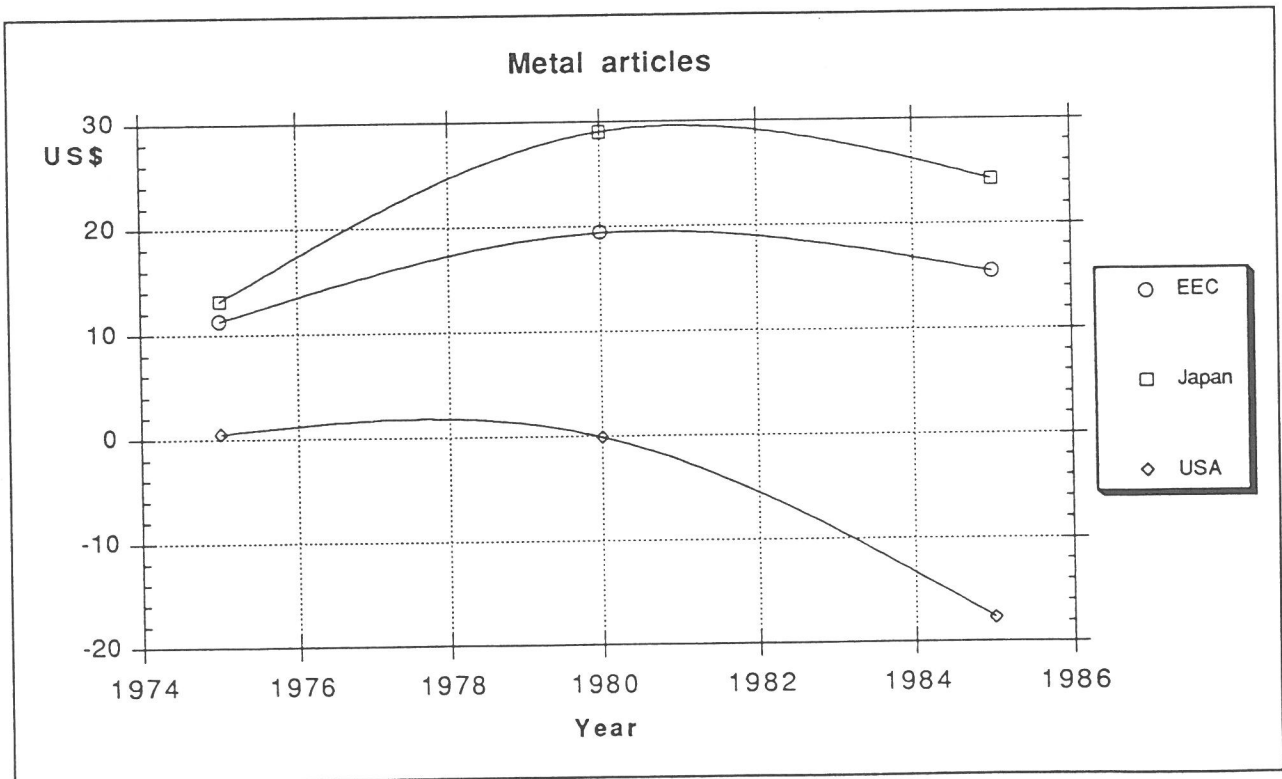


Figure C 6 Trade balance (export minus import per capita at current prices)

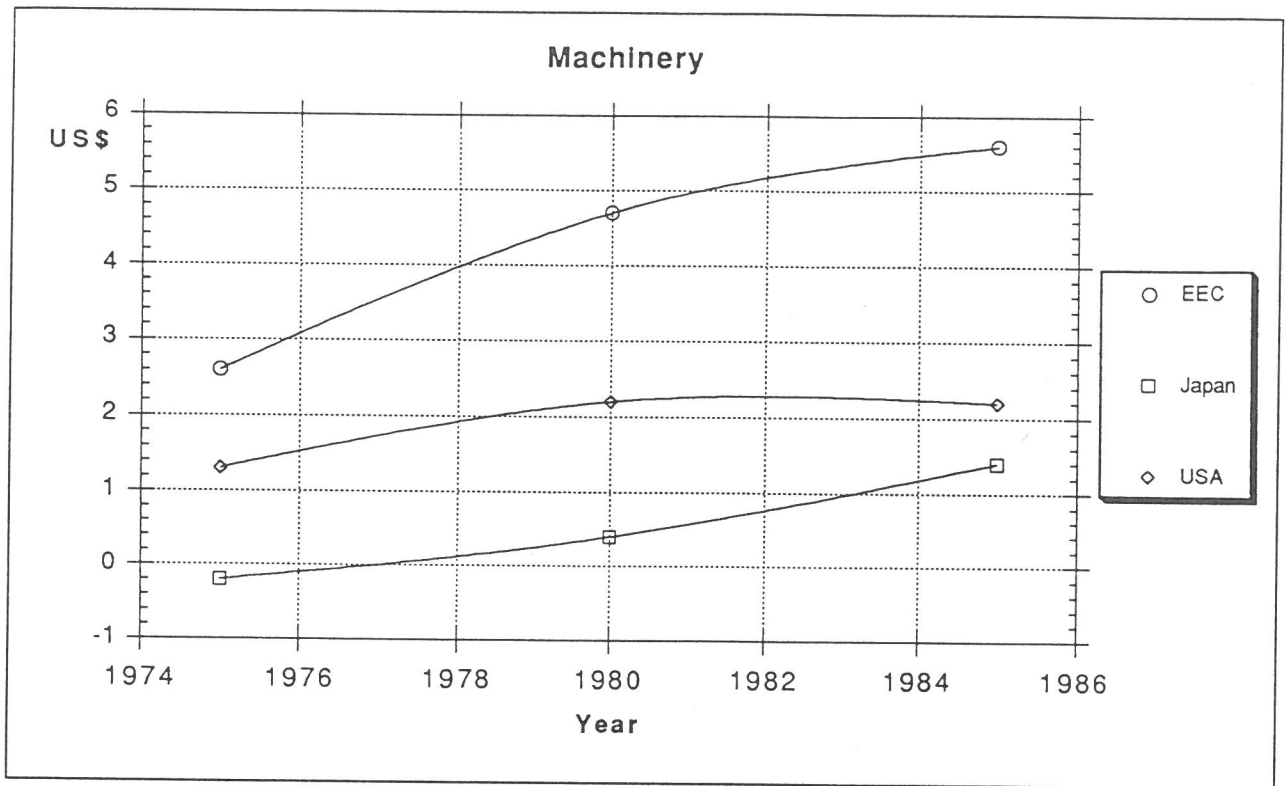


Figure C 7 Trade balance (export minus import per capita at current prices)

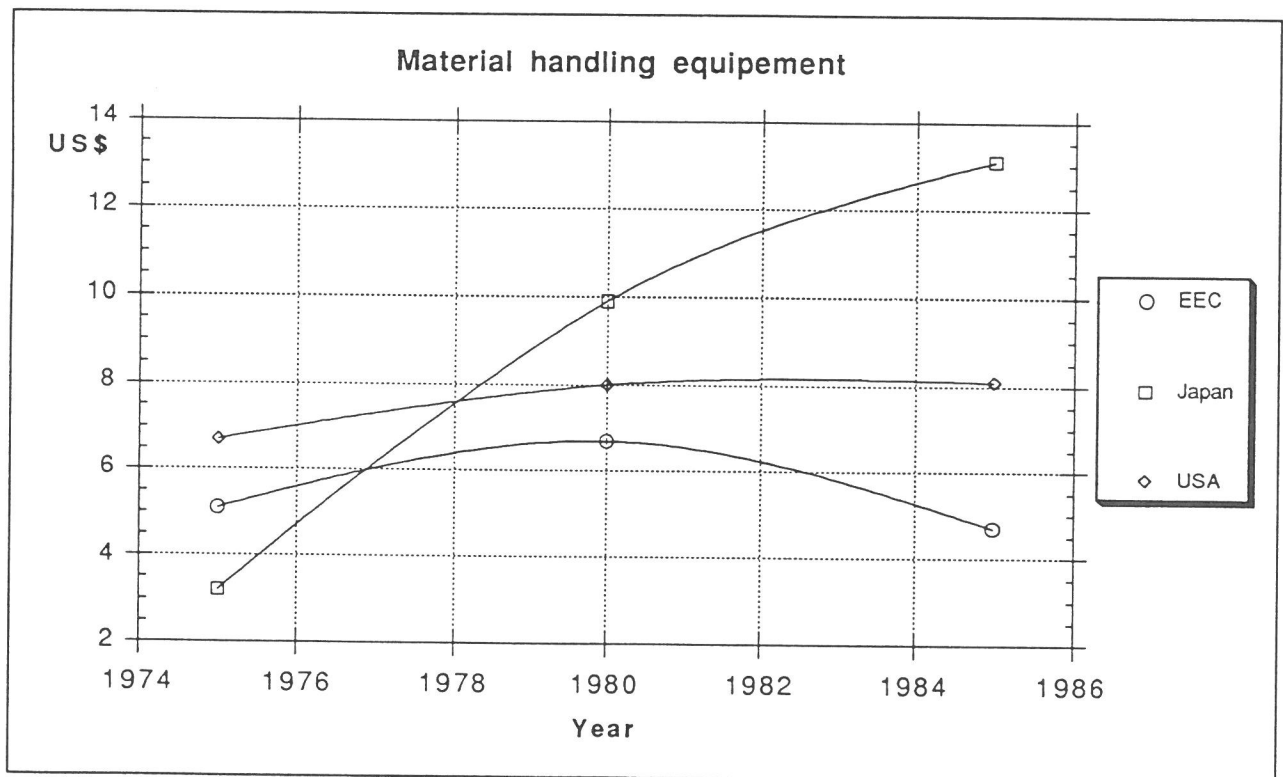


Figure C 8 Trade balance (export minus import per capita at current prices)

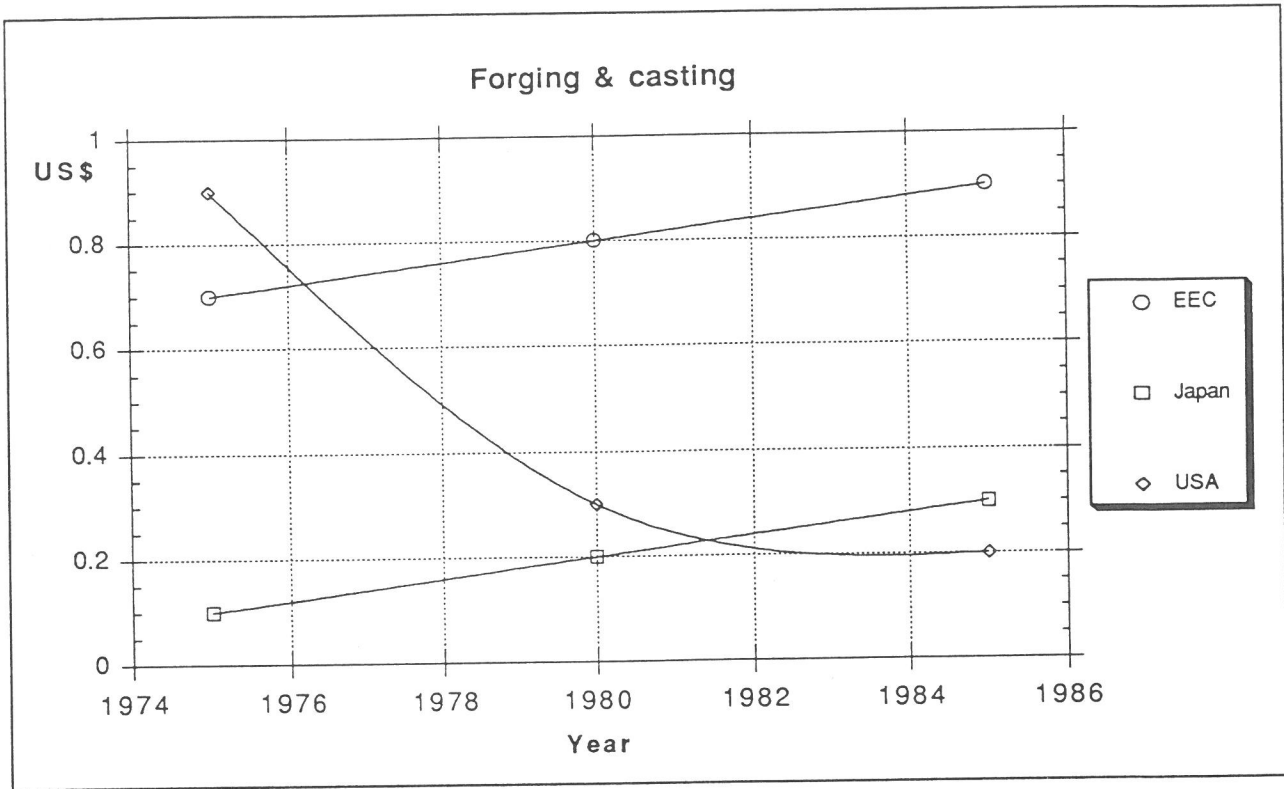


Figure C 9 Trade balance (export minus import per capita at current prices)

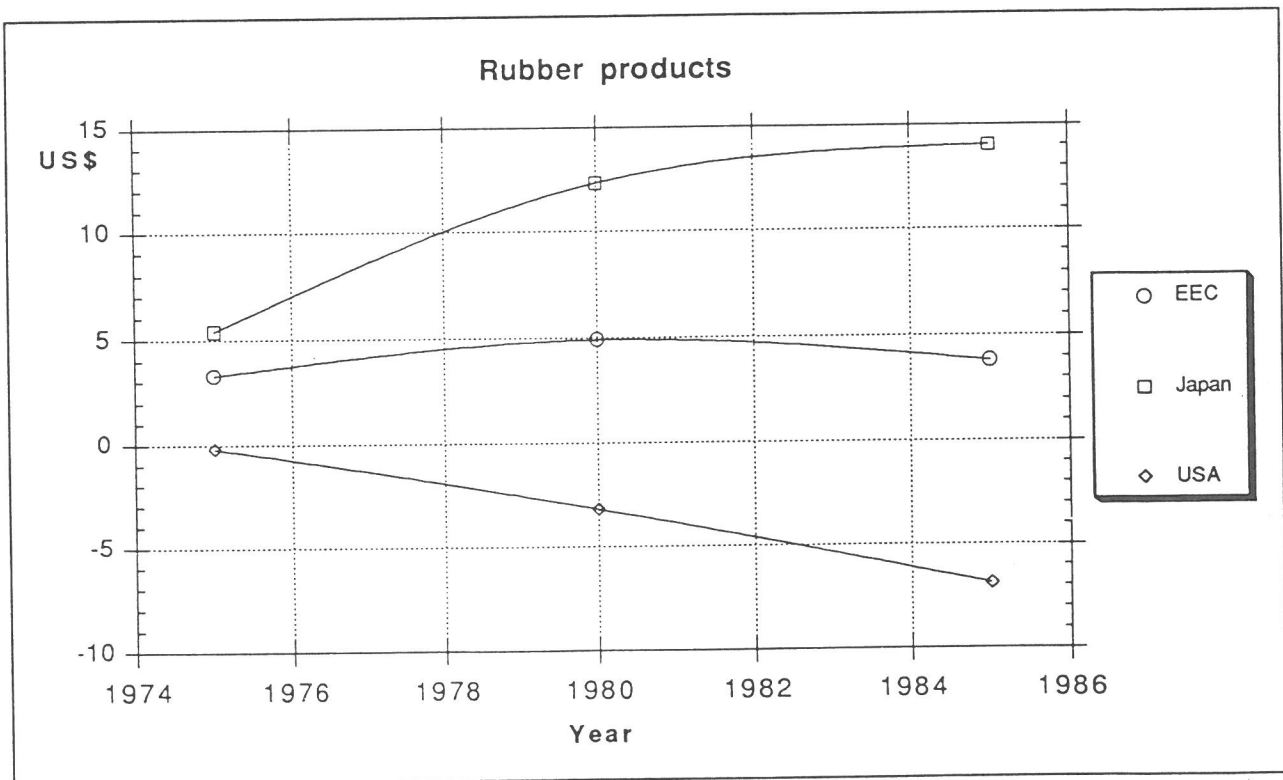


Figure C 10 Trade balance (export minus import per capita at current prices)

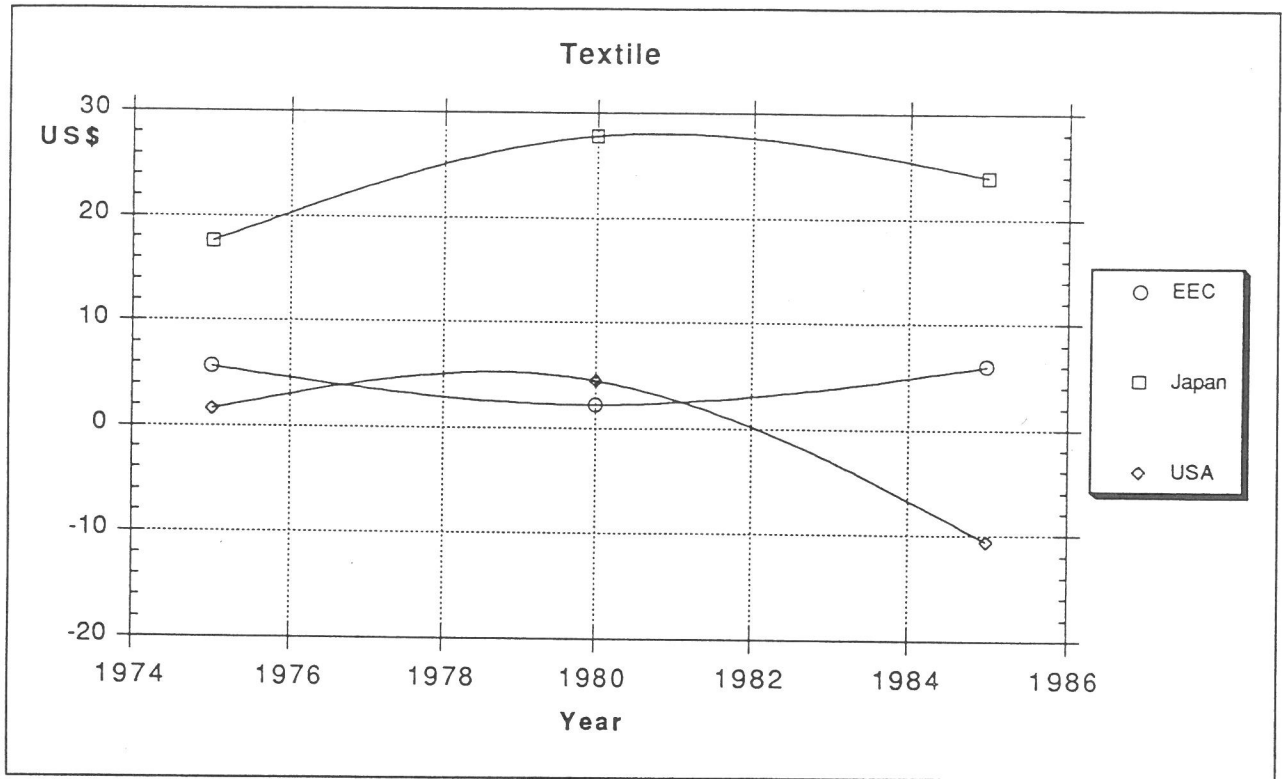


Figure C 11 Trade balance (export minus import per capita at current prices)

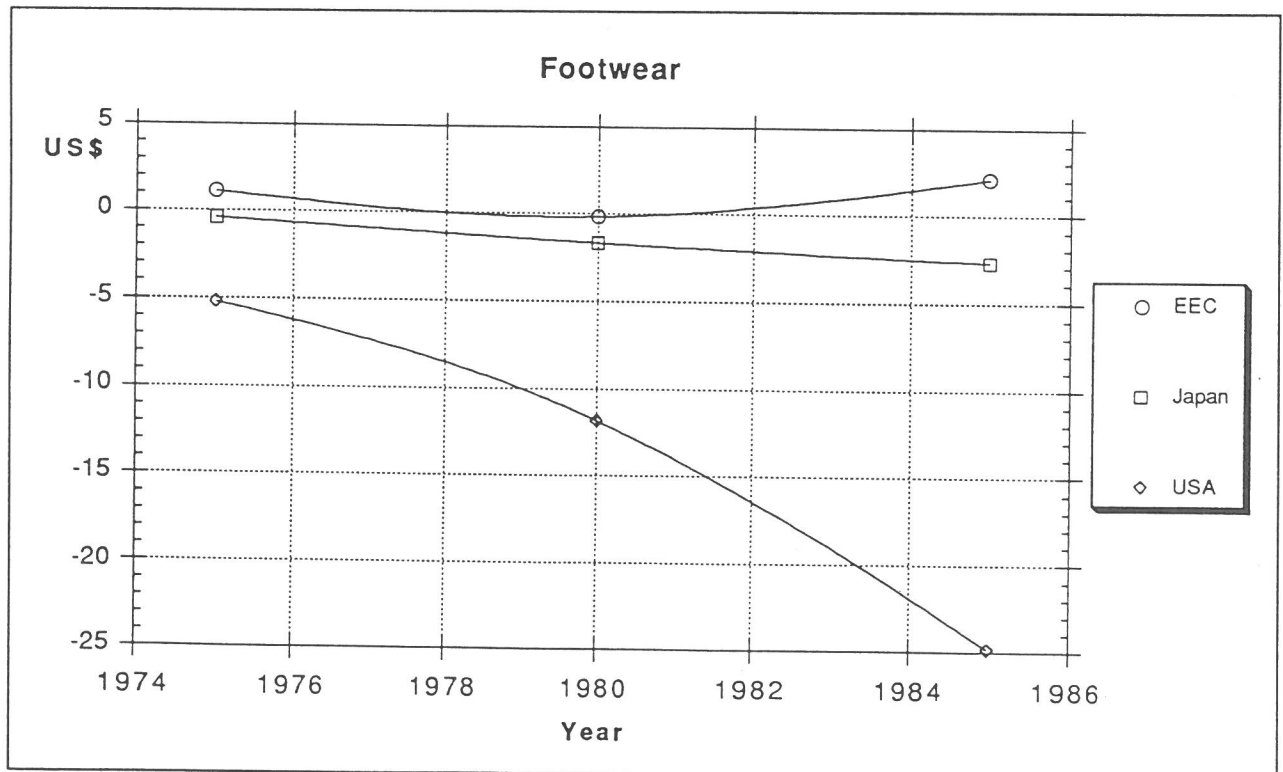


Figure C 12 Trade balance (export minus import per capita at current prices)



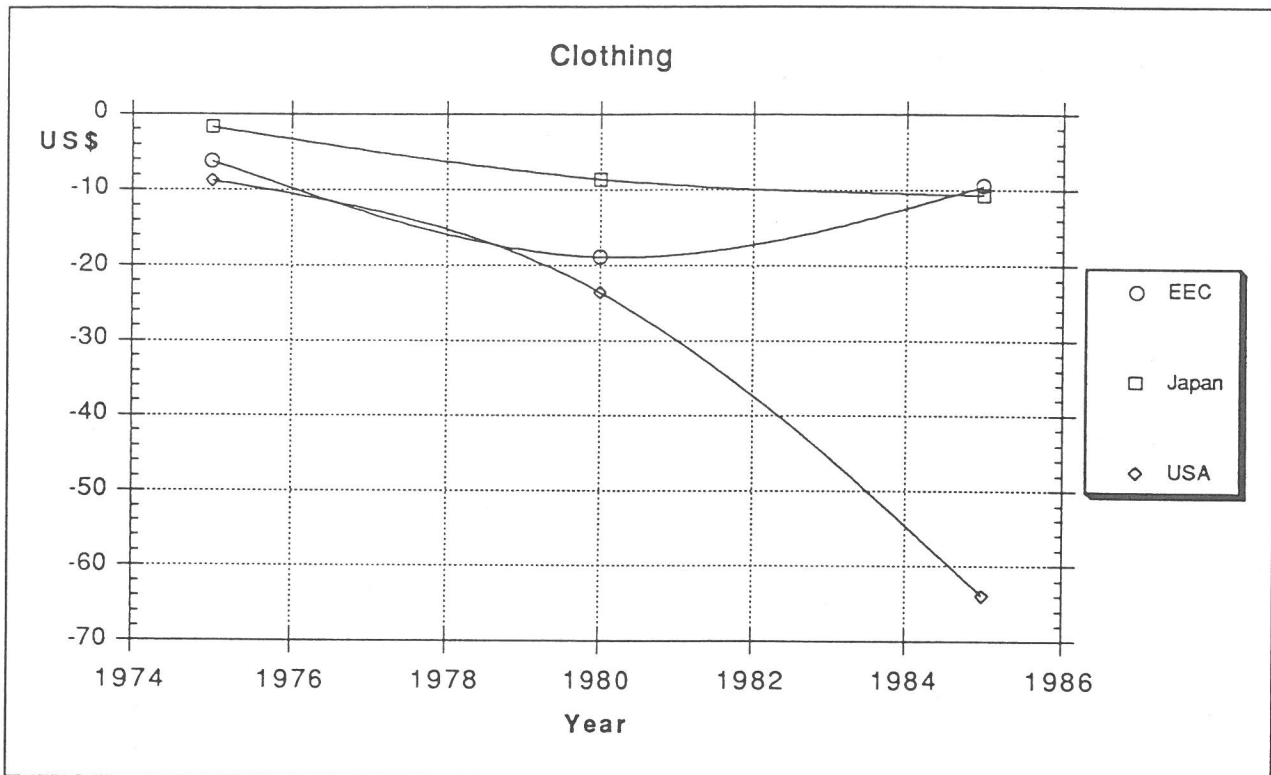


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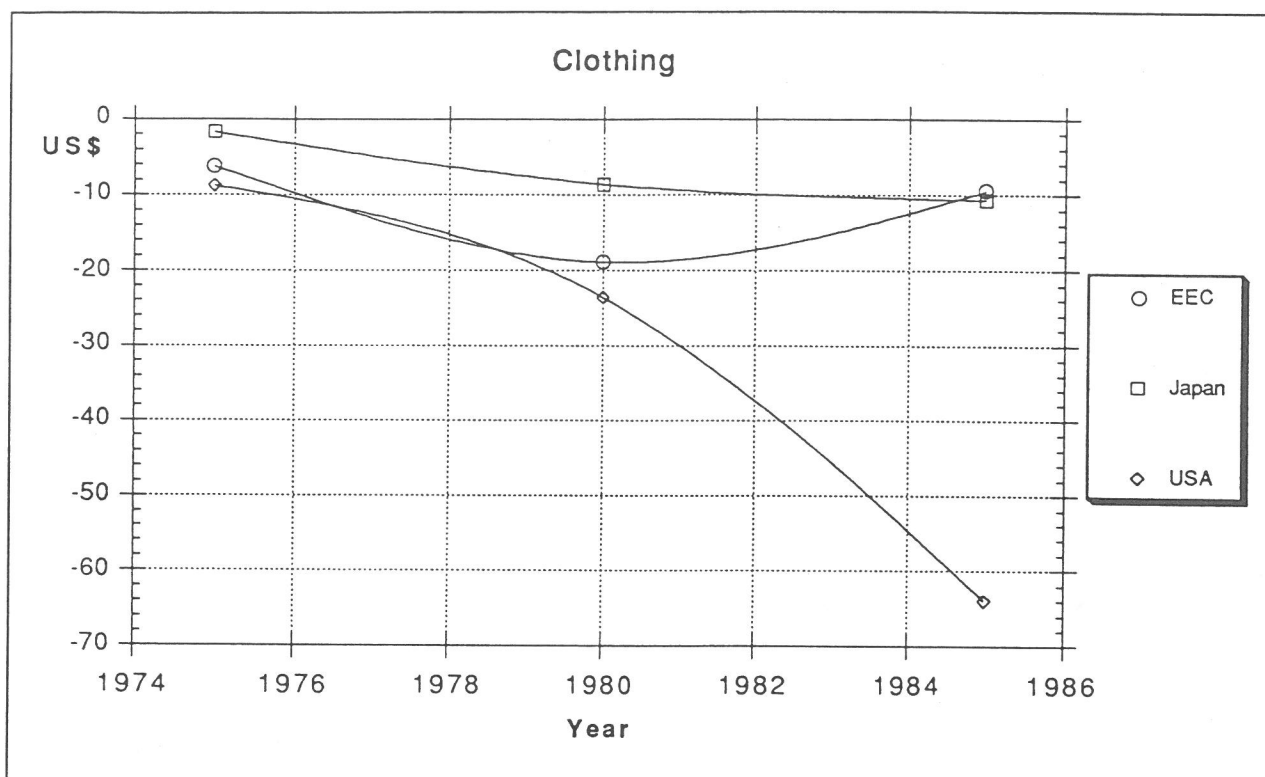


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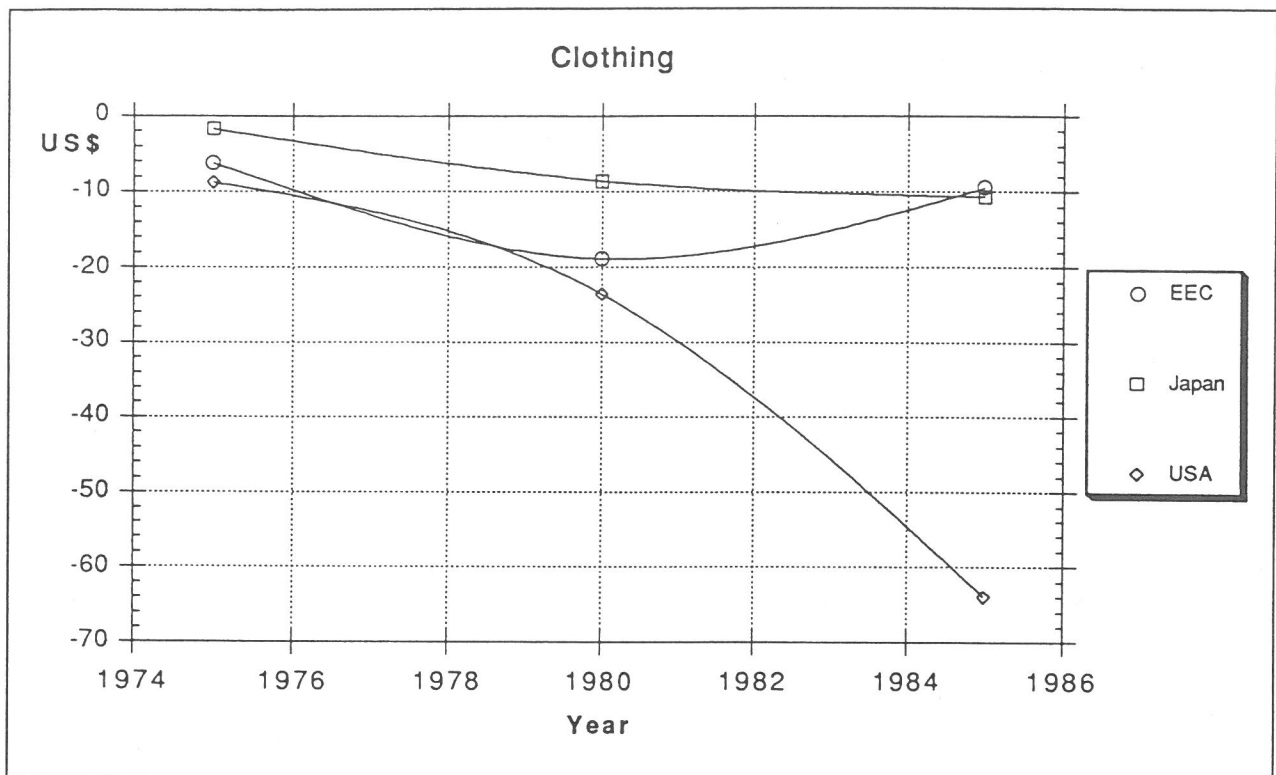


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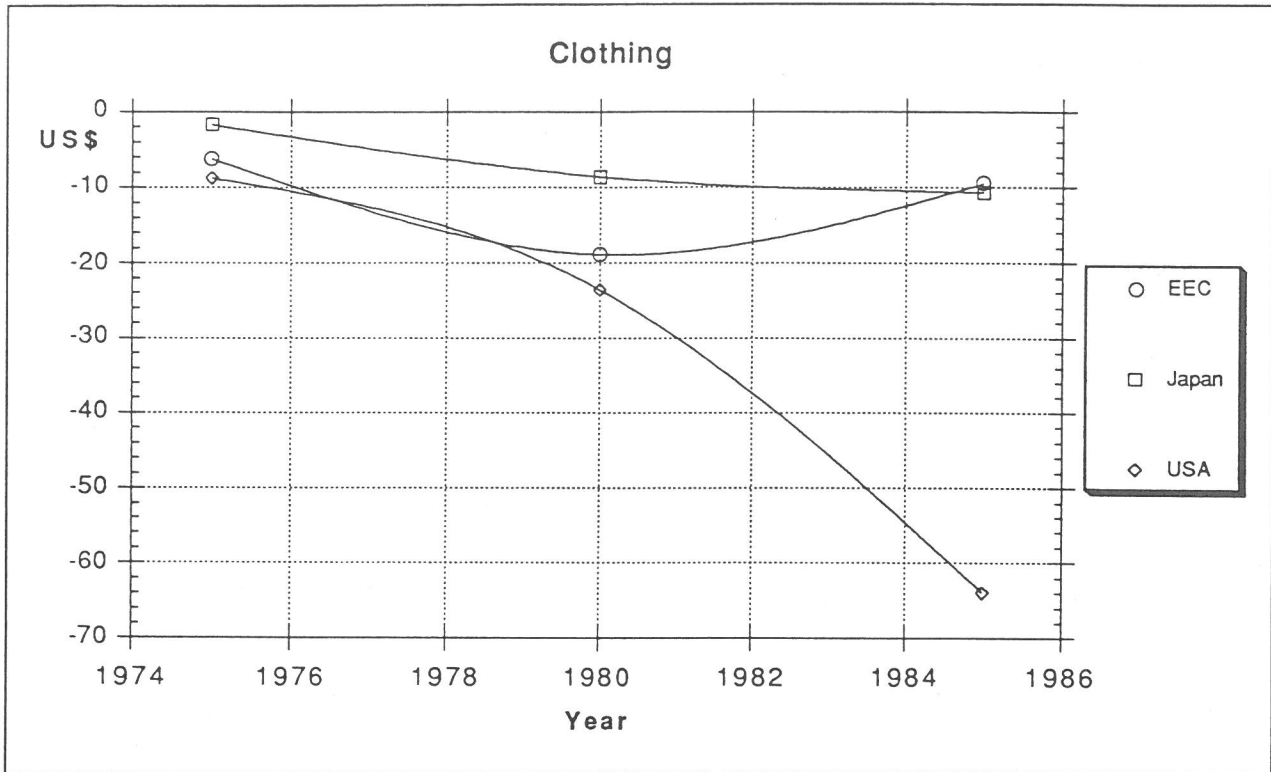


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### **(a) Evaluation of the Raw Materials Programme**

For the raw materials sector which is a business of about 50 billion ECU there appears to be a need for a coherent R&D policy to prevent Europe becoming a "dematerialized society" and to give improved strategic equilibrium between basic and manufacturing industries. Whereas the technical content of the programme was of the highest standard, the programme structure was fragmented and covered a wide subject area in a sporadic way. The following general improvements were suggested:

- Broadening of activities to encompass more generic and "common" problems including multi-disciplinary actions;
- The awarding of the bulk of the project funding to fewer, larger, more generic transnational projects should be stressed.
- The next programme should incorporate a more appropriate subdivision of recycling and other appropriate programmes.

### **(b) Evaluation of the EURAM programme**

The materials sector is estimated to represent 5 to 10 % of the economy of industrialized countries (measured in either sales or employment) with advanced materials representing a modest part (some 5 %) of the total materials market. A reorientation of the programme towards the improvement of traditional materials (new versions, new technologies) and topics related to quality are recommended together with a better balance between the long and the short term, the development of new materials and the promotion of more established materials. Co-operation between producer industry and user industry may prove even more necessary to update various technological parameters and refocus research in materials which are often "systems". In addition, other often more important factors must be considered, like waste disposal, recycling of materials, etc. Future research expectations are assumed to concern:

- (i) Possible new applications,
- (ii) Improved product efficiency and quality,
- (iii) Replacement of existing products,
- (iv) Thorough understanding of properties (esp. for ceramics),
- (v) Reduction of costs.

### **(c) Evaluation of the BRITE programme**

The orientation towards established industry and production technologies which are the largest employers in Europe should be continued. Europe has a strong R&D base, but weakness in management and application of technology, therefore, more attention must be paid to the economic significance and strategic management of projects. Focus should be on all aspects of R&D to improve quality and reduce costs, as well as on new products and processes. The projects must be "pulled through" by the market not "pushed through" by researchers. Research programmes for generic (i.e. "basic") technologies which are critical for many industries, but nevertheless common to several branches, should be continued, avoiding sectoral policies or support for particular industrial sectors. Considering the total of the research programme (100 %) the benefit of the R&D work is expected in multiple nominations with respect to the following areas:

- (i) New or improved products (43 %),
- (ii) Improved quality of products (41 %),
- (iii) New or improved processes (40 %),
- (iv) Accelerated development (32 %),
- (v) Reduced costs of production, maintenance (26 %).

With respect to future aspects of R&D activities in industrial and materials research in the EC it is especially interesting to analyze the topics of the research proposals submitted for support within the BRITE/EURAM in 1989. Figure C14 shows the distribution of technical areas for industrial applied research. It can be seen that about half of the projects can be related to the following broad aspects:

- Manufacturing, including shaping, assembly, joining (24 %)
- Quality, reliability (16 %)
- Process and product assurance (10 %)

In contrast, the proposed areas for focused fundamental research - to be performed by universities and research institutes - concentrate at about 50 % on the functional and special applications of materials, see Figure C15.

This again underlines the key enabling role of materials science and engineering for contemporary industrial technologies.

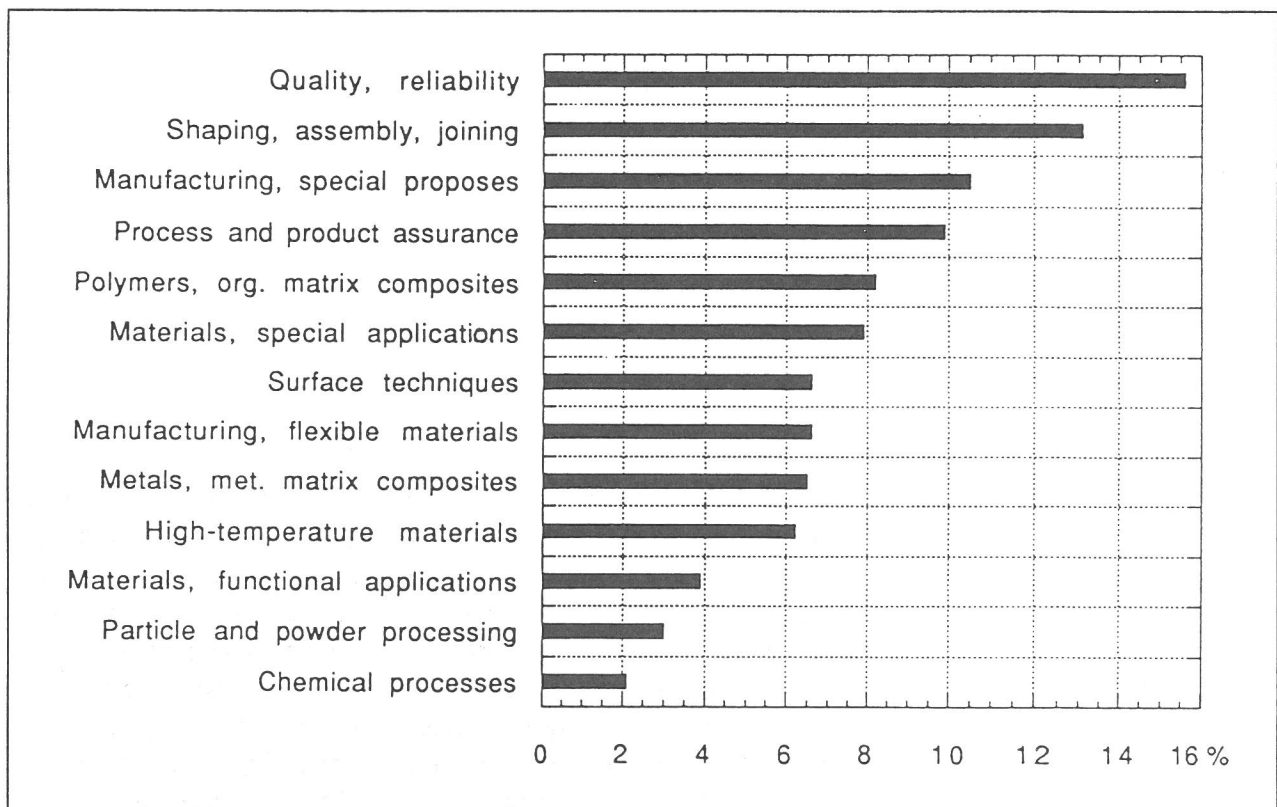


Figure C14 Proposed areas for industrial applied research (BRITE/EURAM Type 1 projects; 2845 entries = 100 %)

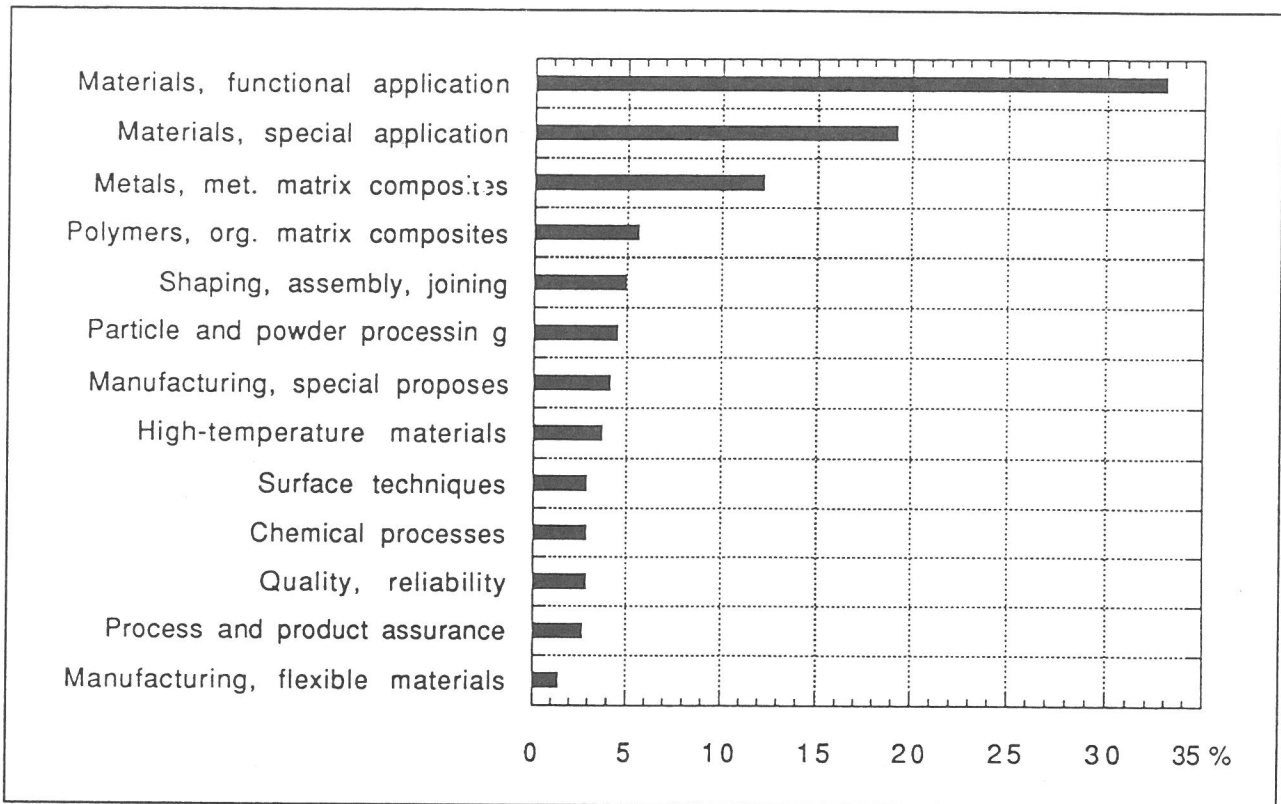


Figure C 15 Proposed areas for focused fundamental research (BRITE/EURAM Type 2 projects; 485 entries = 100 %)

## Acknowledgements

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# References

## Chapter 1

- 1.1 Panorama of EC Industry 1990; Luxembourg: Office for Official Publications of the European Communities 1990
- 1.2 Organization for Economic Co-Operation and Development (OECD): New Technologies in the 1990's; Paris, OECD, 1988, 126 pages
- 1.3 Organization for Economic Co-Operation and Development (OECD): Advanced Materials - Policies and Technological Changes; Paris, OECD, 1990, 187 pages
- 1.4 Czichos, H.; Vitro, R.A.; Lexow, J.F. and Eade, D.P. (Editors): Materials Technology and Development; Advance Technology Alert System (ATAS) Bulletin 5; United Nations, New York, May 1988, 156 pages
- 1.5 Murthy, M.K. and Taylor, S.: Substitutes resulting from advances in materials technologies; in: Ref. 1.4, p. 88-93
- 1.6 Kürsten, M; Blümel, G.; Lahner, L. and Schmidt, H.: Raw materials resources; in Ref. 1.43, p 24-30
- 1.7 Ullmann, B.: New Materials market outlook; Bureau d'Informations et de Prévisions Economiques (BIPE), Neuilly-sur Seine, France, 1989

## Chapter 2

- 2.1 Materials Research Advisory Committee: Trends and opportunities in materials research; US National Science Foundation, Washington, 1984
- 2.2 Edmonds, D.V.: New materials and developments in materials technology, in: Enhancement of transfer of technology to developing countries. Advisory Committee on Health Research (ACHR), World Health Organization, Geneva, 1987
- 2.3 Ashby, M.F. and Jones, D.R.H.: Ingenieurwerkstoffe, Berlin: Springer-Verlag, 1986
- 2.4 Flemings, M.C.: Structural materials: metals, ceramics, polymers and composites; in Ref 1.4, p. 31-42

- 2.5 Cohen, M.: Progress and prospects in metallurgical research; in: *Advancing Materials Research* (Psaras, P.A. and Langford, H.D., Editors), Washington: National Academy Press, 1987, p. 51-110
- 2.6 van Griethuysen (Editor): *New application of materials; Forecasting and Assessment in Science and Technology (FAST) Report No. 203*, Commission of the European Communities, Brussels, September 1987
- 2.7 Birringer, R. and Gleiter, H.J.: *Nanokristalline Materialien*; in: *Neue Werkstoffe, Band 1*, Düsseldorf: VDI-Verlag, 1988, S. 95-108
- 2.8 Flemings, M.C.: *Functional materials: electronics, information and sensors*; in Ref. 1.4, p. 43-48
- 2.9 McG. Tegart, W.J.: *Civil engineering materials: cement, concrete and plaster*; in Ref. 1.4, p. 48-53
- 2.10 Deppe, H.-J.: *Renewable materials: wood and wood-based materials*; in Ref. 1.4, p. 53-55  
2.11 Chopplet, M. and Thiery, J.-P.: *Biomedical materials*; in Ref. 1.4, p. 56-59

## Chapter 4

- 4.1 Czichos, H.: *Materials Research and Testing - Development Trends and Outline Proposal for a Community Programme "Basic Technological Research"*; Berlin: Bundesanstalt für Materialprüfung, Forschungsbericht 85, Oct. 1982

## ANNEX

- A1 *Materials and Man's Needs - Materials Science and Engineering (Summary Report of the Committee on the Survey of Materials Science and Engineering, COSMAT)*. Washington: National Academy of Science, 1974, 217 p.
- A2 Psaras, P.A. and Langford, H.D. (Editors): *Advancing Materials Research*. Washington: National Academy Press, 1987, p 25-48
- A3 National Academy of Science: *Science and Technology - A Five-Year Outlook, Chapter 2 "Materials"*, San Francisco: W.H. Freeman & Co, 1979, p. 301-340
- A4 Slivka, D.C., Frische, R. and Yanase, Y.: *Innovative materials. An evaluation of commercial developments in Europe, Japan and the United States*. Battelle (USA), 1985.
- A5 *The MIT Commission on Industrial Productivity: Made in America - Regaining the Productive Edge*. Cambridge, Mass.: The MIT Press, 1989

- A6 National Research Council: Materials Science and Engineering for the 1990's - Maintaining, Competitiveness in the Age of Materials, Washington: National Academy Press, 1989
- B1 Japan External Trade Organization (JETRO): New products resulting from advances in materials technologies, in Ref. 1.4, p. 80-87
- B2 Nii, K.: National Policy on Materials Research and Development in Japan. Lecture notes, World Materials Congress, Chicago 1988, Tokyo: National Research Institute for Metals
- C1 Andersen, A.: Performance of the European manufacturing industry; Bruxelles: Commission of the European Communities, DG XII, Febr. 1988.

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**Untersuchungen zur Zerfallsfähigkeit von Distickstoffoxid**
- Nr. 90/ISBN 3-88314-264-6/1983  
K. Brandes, E. Limberger, J. Herter  
**Kinetische Grenztragfähigkeit von stoßartig belasteten Stahlbetonbauteilen**  
**Kinetic Load Bearing Capacity of Impulsively Loaded Reinforced Concrete Members**
- Nr. 91/ISBN 3-88314-265-4/1983  
M. Weber  
**Dreidimensionale Analyse von unbewehrtem Beton mit nichtlinear-elastischem Materialgesetz**
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L. Auersch  
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P. Studt  
**Unterdrückung stick-slip-induzierter Kurvengeräusche schienengebundener Fahrzeuge durch eine physikalisch-chemische Oberflächenbehandlung der Schienen**
- Nr. 94/ISBN 3-88314-284-0/1983  
Xian-Quan Dong  
**Untersuchungen der Störerschwingungen beim Kerbschlagbiegeversuch und deren Abschwächungen**
- Nr. 95/ISBN 3-88314-289-1/1983  
M. Römer  
**Über die Fokussierung des Schallfeldes von Ultraschall-Prüfköpfen mit Fresnelschen Zonenplatten**
- Nr. 96/ISBN 3-88314-296-4/1983  
H. Eifler  
**Verbundverhalten zwischen Beton und geripptem Betonstahl sowie sein Einfluß auf inelastische Verformungen biegebeanspruchter Stahlbetonbalken**
- Nr. 97/ISBN 3-88314-297-2/1983  
G. Fuhrmann, W. Schwarz  
**Typische Bruchflächenbildung thermoplastischer Kunststoffge nach wechselnder mechanischer Beanspruchung**
- Nr. 98/ISBN 3-88314-312-X/1983  
E. Schnabel  
**Bestimmung des elastischen Verhaltens von Maschinenwaren**  
**- Stretch- und Erholungsvermögen -**
- Nr. 99/ISBN 3-88314-317-0/1983  
K. Brandes, E. Limberger, J. Herter  
**Kinetische Grenztragfähigkeit von Stoßartig belasteten Stahlbetonbauteilen**  
**Kinetic Load Bearing Capacity of Impulsively Loaded Reinforced Concrete Members**
- Nr. 100/ISBN 3-88314-298-0/1984  
G. Klamrowski, P. Neustupny  
**Untersuchungen zur Prüfung von Beton auf Frostwiderstand**
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P. Reimers, J. Goebbels, H. Heidt, P. Weise, K. Wilding  
**Röntgen- und Gammastrahlen Computer-Tomographie**
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G. Magiera  
**Weiterentwicklung des hydraulischen Kompensationsverfahrens zur Druckspannungsmessung in Beton**
- Nr. 103/ISBN 3-88314-328-6/1984  
D. Schnitger  
**Radiographie mit Elektronen aus Metallverstärkerfolien**
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M. Gierloff  
**Beeinflussung von Betoneigenschaften durch Zusatz von Kunststoffdispersionen**
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B. Schulz-Forberg  
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J. Lehnert  
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W. Stichel, J. Ehreke  
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L. Auersch  
**Durch Bodenerschütterungen angeregte Gebäudeschwingungen - Ergebnisse von Modellrechnungen**
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M. Omar  
**Zur Wirkung der Schrumpfbehinderung auf den Schweißspannungszustand und das Sprödbruchverhalten von unterpulvergeschweißten Blechen aus St E 460 N**
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H. Walde, B. Kropp  
**Wasserstoff als Energieträger**
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K. Ziegler  
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W. Lützow  
**Zeitstandverhalten und strukturelle Veränderungen von vielfach wiederverarbeiteten Polyethylenen**
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R. Helms, H. Henke, G. Oelrich, T. Saito  
**Untersuchungen zum Frequenzeinfluß auf die Schwingungskorrosion von Offshore-Konstruktionen**

- Nr. 114/ISBN 3-88314-419-3/1985  
P. Rose, P. Raabe, W. Daum, A. Szameit  
**Neue Verfahren für die Prüfung von Reaktorkomponenten mittels Röntgen- und Gammastrahlen**
- Nr. 115/ISBN 3-88314-420-7/1985  
K. Richter  
**Farbempfindungsmerkmal Elementaruntun und Buntheitsabstände als Funktion von Farbart und Leuchtdichte von In- und Umfeld**
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F.-J. Kasper, R. Müller, R. Rudolphi, A. Wagner  
**Theoretische Ermittlung des Wärmedurchgangskoeffizienten von Fensterkonstruktionen unter besonderer Berücksichtigung der Rahmenproblematik**
- Nr. 117/ISBN 3-88314-468-1/1985  
H. Czichos, G. Sievers  
**Materials Technologies and Techno-Economic Development  
A Study for the German Foundation for International Development (Deutsche Stiftung für Internationale Entwicklung)**
- Nr. 118/ISBN 3-88314-469-X/1985  
H. Treumann, H. Andre, E. Blossfeld, N. Pfeil, M.-M. Zindler  
**Brand- und Explosionsgefahren explosionsgefährlicher Stoffe bei Herstellung und Lagerung. Modellversuche mit pyrotechnischen Sätzen und Gegenständen**
- Nr. 119/ISBN 3-88314-472-X/1985  
J. Herler, K. Brandes, E. Limberger  
**Kinetische Grenztragfähigkeit von stoßartig belasteten Stahlbetonbauteilen  
Versuche an Stahlbetonplatten, Teil I  
Kinetic Load Bearing Capacity of Impulsively Loaded Reinforced Concrete Members  
Tests on Reinforced Concrete Slabs, Part I**
- Nr. 120/ISBN 3-88314-514-9/1986  
A. Hecht  
**Zerstörungsfreie Korngrößenbestimmung an austenitischen Feinblechen mit Hilfe der Ultraschallrückstreuung**
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P. Feinle, K.-H. Habig  
**Versagenskriterien von Stahlgleitpaarungen unter Mischreibungsbedingungen: Einflüsse von Stahlzusammensetzung und Wärmebehandlung**
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J. Mischke  
**Entsorgung kerntechnischer Anlagen.  
Sonderkolloquium der Bundesanstalt für Materialprüfung (BAM) am 10. 12. 1985 mit Beiträgen von B. Schulz-Forberg, K.E. Wieser und B. Droste**
- Nr. 123/ISBN 3-88314-531-9/1986  
D. Rennoch  
**Physikalisch-chemische Analyse sowie toxische Beurteilung der beim thermischen Zerfall organisch-chemischer Baustoffe entstehenden Brandgase**
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H.-M. Thomas  
**Zur Anwendung des Impuls-Wirbelstromverfahrens in der zerstörungsfreien Materialprüfung**
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B. Droste, U. Probst  
**Untersuchungen zur Wirksamkeit der Brandschutzisolierung von Flüssiggas-Lagertanks**
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W. Stichel  
**Korrosion und Korrosionsschutz von Metallen in Schwimmbädern**
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E. Limberger, K. Brandes, J. Herter, K. Berner  
**Kinetische Grenztragfähigkeit von stoßartig belasteten Stahlbetonbauteilen  
Kinetic Load Bearing Capacity of Impulsively Loaded Reinforced Concrete Members  
Versuche an Stahlbetonbalken, Teil I  
Tests on Reinforced Concrete Beams, Part I**
- Nr. 128/ISBN 3-88314-568-8/1986 (vergriffen)  
E. Limberger, K. Brandes, J. Herter, K. Berner  
**Kinetische Grenztragfähigkeit von stoßartig belasteten Stahlbetonbauteilen  
Kinetic Load Bearing Capacity of Impulsively Loaded Reinforced Concrete Members  
Versuche an Stahlbetonbalken, Teil II  
Tests on Reinforced Concrete Beams, Part II**
- Nr. 129/ISBN 3-88314-569-6/1980 (vergriffen)  
K. Brandes, E. Limberger, J. Herter, K. Berner  
**Kinetische Grenztragfähigkeit von stoßartig belasteten Stahlbetonbauteilen  
Kinetic Load Bearing Capacity of Reinforced Concrete Members under Impact Load**
- Zugversuche an Betonstahl mit erhöhter Dehngeschwindigkeit  
Reinforcing Steel Tension Tests with high strain rates**  
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W. Struck  
**Einfache Abschätzung der Durchbiegung und der Energieaufnahme von Trägern aus duktilem Material bei Belastung durch eine Einzelkraft**
- Nr. 131/ISBN 3-88314-585-8/1986  
E. Limberger, K. Brandes, J. Herter  
**Kinetische Grenztragfähigkeit von stoßartig belasteten Stahlbetonbauteilen  
Kinetic Load Bearing Capacity of Reinforced Concrete Members under Impact Load  
Versuche an Stahlbetonplatten, Teil II  
Tests on Reinforced Concrete Slabs, Part II**
- Nr. 132/ISBN 3-88314-595-5/1987  
Chr. Herold, F.-U. Vogdt  
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G. Andreae, G. Niessen  
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J. Ludwig, W.-D. Mischke, A. Ulrich  
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H.-J. Deppe, K. Schmidt  
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D. Aurich  
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M. Dogunke, F. Buchhardt  
**Zur geowissenschaftlichen Einordnung des Gebietes der Bundesrepublik Deutschland und einer sicheren Auslegung technischer Systeme gegen den Lastfall Erdbeben.**
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J. Olschewski, S.-P. Scholz  
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- Nr. 140/ISBN 3-88314-643-9/1987  
K. Brandes, E. Limberger, J. Herter  
**Kinetische Grenztragfähigkeit von stoßartig belasteten Stahlbetonbauteilen  
Kinetic Load Bearing Capacity of Impulsively Loaded Reinforced Concrete Members**
- Nr. 141/ISBN 3-88314-694-3/1987  
F. Buchhardt, W. Matthees, G. Magiera, F. Mathiak  
**Zum Einfluß des Sicherheits- und Auslegungserdbebens auf die Bemessung von Kernkraftwerken**
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H. Treumann, G. Krüger, N. Pfeil, S. von Zahn-Ullmann  
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K. Brandes, E. Limberger, J. Herter  
**Kinetische Grenztragfähigkeit von stoßartig belasteten Stahlbetonbauteilen  
Kinetic Load Bearing Capacity of Impulsively Loaded Reinforced Concrete Members  
Experimentelle und numerische Untersuchungen zum Trag- und Verformungsverhalten von Stahlbetonbauteilen bei Stoßbelastung  
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F. Buchhardt, G. Magiera, W. Matthees, M. Weber, J. Altes  
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U. Holzöhner  
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W. Schön, M. Mallon  
**Untersuchungen zur Wirksamkeit von Wasserberieselungseinrichtungen als Brandschutzmaßnahme für Flüssiggas-Lagertanks**
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H.-D. Kleinschrodt  
**Lösung dynamischer Biege- und Torsionsprobleme von Stabsystemen aus dünnwandigen elastischen Stäben mit offenem Querschnitt mittels frequenzabhängiger Ansatzfunktionen**
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W. Müller  
**Theoretische Untersuchung von Variationsprinzipien für elastoplastisches Materialverhalten sowie Entwicklung und numerische Erprobung von Finite-Element-Verfahren für den ebenen Spannungszustand**
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U. Holzöhner  
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M. Weber  
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L. Auersch-Saworski  
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G. Plauk, G. Kretschmann, R.-G. Rohrmann  
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H. Sander, W.-W. Maennig  
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K. Breitkreutz, R. Uttech, K. Haedecke  
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L. Auersch  
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G. Klamrowski, P. Neustupny, H.-J. Deppe, K. Schmidt, J. Hundt  
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E. Limberger, K. Brandes  
**Versuche zum Verhalten von Stahlbetonbalken mit Übergreifungsstößen der Zugbewehrung unter stoßartiger Belastung**
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R. Wäsche, K.-H. Habig  
**Physikalisch-chemische Grundlagen der Feststoffschmierung - Literaturübersicht -**
- Nr. 159/ISBN 3-88314-890-3/1989  
R. Müller, R. Rudolphi  
**Berechnung des Wärmedurchlaßwiderstandes und der Temperaturverteilung im Querschnitt von Haus-schornsteinen nach DIN 18160 Teil 6**
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W. Matthees  
**Entwicklung eines Makroelementes durch Kondensation am Beispiel der Lastfälle Flugzeugabsturz und Erdbeben bei Boden-Bauwerk-Wechselwirkung mit biegeweichen Fundamenten**
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G. Mellmann, M. Maultzsch  
**Untersuchung zur Ermittlung der Biegefestigkeit von Flachglas für bauliche Anlagen**
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W. Brünner  
**Untersuchungen zur Tragfähigkeit großer Glasscheiben**
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W. Brünner, G. Mellmann, W. Struck  
**Biegefestigkeit und Tragfähigkeit von Scheiben aus Flachglas für bauliche Anlagen**
- Nr. 164/ISBN 3-88314-934-9/1989  
R. Helms, B. Jaenicke, H. Wolter, C.-P. Bork  
**Zur Schwingfestigkeit großer geschweißter Stahlträger**

- Nr. 165/ISBN 3-88314-935-7/1989  
P. Göbel, L. Meckel, W. Schiller  
**Untersuchung zur Erarbeitung von Kennwerten bei  
Einrichtungsmaterialien (Holzwerkstoffen, Möbeln  
und Textilien) hinsichtlich der Formaldehyd-  
Emission.**  
**Teil B: Textilien**
- Nr. 166/ISBN 3-88314-936-5/1989  
K. Breitzkreutz  
**Modelle für Stereologische Analysen**
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A. Mitakidis, W. Rücker  
**Erschütterungsausbreitung im elastischen Halbraum  
bei transienten Belastungsvorgängen**
- Nr. 168/ISBN 3-88314-958-6/1990  
F.-J. Kasper, R. Müller, R. Rudolphi  
**Numerische Untersuchung geometriebedingter Wär-  
mebrücken (Winkel und Ecken) unter Einsatz hoch-  
auflösender Farbgraphik bei Berücksichtigung der  
Tauwasserproblematik und des Mindestluftwechsels**
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Chr. Kohl, W. Rücker  
**Integration der Untergrunddynamik in das Programm-  
system MEDYNA, dargestellt am Beispiel des Intercity  
Experimental (ICE)**
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P. Studt, W. Kerner, Tin Win  
**Untersuchung der mikrobiologischen Schädigung  
wassergemischter Kühlschmierstoffe mit dem Ziel  
der Verbesserung der Arbeitshygiene, der Minderung  
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der Emulsionen**
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F. Buchhardt  
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namischer Systeme am Beispiel der Boden-Bauwerk-  
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W. Brocks, D. Klingbeil, J. Olschewski  
**Lösung der HRR-Feld-Gleichungen der elastisch-pla-  
stischen Bruchmechanik**
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Hochtemperatur-Dehnungsaufnehmers für Einsatz-  
temperaturen bis ca. 1000 °C**
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H. Eifler  
**Die Drehfähigkeit plastischer Gelenke in Stahlbeton-  
Plattenbalken, bewehrt mit naturhartem Betonstahl  
BSt 500 S im Bereich negativer Biegemomente**
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E. Klement, G. Wieser  
**Zur numerischen Übertragbarkeit von Prüfungser-  
gebnissen an Hausschornsteinen auf Schornsteine  
mit anderen lichten Querschnitten**
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