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シュツッツガルト、マックス・プランク金属研究所名誉所長
ギュンター・ペツオー教授

New Materials in the Service of mankind

Prof. Dr. Günter Petzow
Max-Planck-Institute for Metals Research, Stuttgart

財団法人 本田財団

ギュンター・E・ペツオー

マックス・プランク金属研究所名誉所長
シュツッツガルト大学名誉教

Günter E. Petzow

Director emeritus the Max-Planck-Institute for Metals Research
Honorar Professor, University of Stuttgart

■略歴

1926	ドイツに生まれる。
1956	シュツッツガルト大学工学修士
1959	シュツッツガルト大学理学博士
1965～94	マックス·プランク材料科学研究所粉末冶金研究室長
1974～	シュツッツガルト大学名誉教授
1982～95	国立メタログラファー養成学校校長
1984～94	マックス·プランク金属研究所先端セラミックス研究室長
1988～91	ドイツ金属学会会長
1989～92	マックス・プランク金属研究所所長
1994～	マックス・プランク金属研究所名誉所長

■受賞歴

1982	米国国際メタログラフィー学会 ヘンリー・クリフトン・ソルベイ賞
1984	ドイツ金属学会 エミール・ハイン賞
1990	ドイツ連邦共和国 功績十字勲章
1995	勲三等旭日中綬章

■会員

日本金属学会
ドイツ金属学会
欧州科学技術アカデミー

●著書、論文：「材料組織観察法」他600以上

■Personal History

1926	Born in Germany
1956	M.S. in Engineering, University of Stuttgart
1959	Ph.D. in Materials Science, University of Stuttgart
1965～94	Founder and Head of Department of Powder Metallurgy at the Max-Planck-Institute for Materials Science, Stuttgart
1974～	Hon. Professor of the University of Stuttgart
1982～95	Director of the National School for Technicians in Metallography
1984～94	Founder and Head of the Department of Advanced Ceramics at the Max-Planck-Institute for Metals Research
1988～91	President of the German Society for Materials
1989～92	Executive managing Director of the Max-Planck-Institute for Metals Research
1994～	Director emeritus of the Max-Planck-Institute for Metals Research

■Awards

1982	Henry Clifton Sorby Award, International Metallopraphic Society, USA
1984	Heyn-Denkmunze, Highest Destinction of the German Society for materials(DGM)
1990	1st Class Order of Merits from the President of the Federal Republic of Germany
1995	Order of the Rising Sun, Gold Rays with Neck Ribbon from the Japanese Government

■Memberships

Japan Institute of Metals(JIM)
German Society for Materials(DGM)
European Academy for Science and Art

●His more than 600 publications deal with investigations on processing and properties of new inorganic materials.

NEW MATERIALS IN THE SERVICE OF MANKIND

- The Eco-Technological Approach -

Lecture at the conferring ceremony on the 17th of November 1997 in Tokyo

Prof. Dr. Günter Petzow

Max-Planck-Institute for Metals Research, Stuttgart

Mrs. Honda, President Kawashima,
Excellencies, distinguished guests,

Today is a very special day for me on which I feel great joy and deep gratitude. To stand in a row with world famous Honda Prize awardees is a particular honour and an enormous incentive. My heartfelt thanks go to you Mrs. Honda for the wonderful medal and the generous supplementary gift. I am very grateful to you Mr. Kawashima for the very positive eulogy, which I enjoyed listening to in all modesty and of course thanks for the impressive testimonial.
I am especially pleased that the Ambassador of my native country could attend this ceremony, herewith paying tribute to the Honda Foundation as well as to the basic science. Many thanks, Excellency, for your appreciative words. I am aware of the special status of the Council for Science and Technology. The presence of a highly ranked representative of this organisation is an additional distinction. Thank you Mr. Mori for being with us and for your congratulatory address.

I have to thank all those who nominated me for the prize, and those in the appointed circles who critically examined and accepted this nomination. I also would like to express my appreciation to all who have gone to such trouble in arranging this fine event; mainly the excellent staff of the Honda Foundation.

"When you drink water, remember the source" is a saying. And in this sense, thanks are also due to the Max-Planck-Institute for Metals Research, which supported my research work. Therefore this prize is certainly also an acknowledgement for this institute, which many of you know from your own experience.

Of course I would have liked to express my personal thanks to Soichiro Honda today, the magnanimous founder. This prize, which bears his name, connects me to him in a particular way. With the donation of this prize, an idea is being pursued that lay especially close to his heart, namely, to take care that all technologies should be shaped by humanity.

As the first materials scientist who has been granted with the Honda Prize, I decided straight away, that I should set materials at the centre of my lecture and highlight them in the frame of Hondas concept, namely in the frame of eco-technology. Soichiro Honda as son of a blacksmith, felt the fascination of materials already in his youth. With bated breath, so written in the book "Honda about Honda" [1], he watched as a boy the working of glowing iron, from which sparks sprayed. "Imperceptibly," he wrote, "awoke my understanding for the material and then for the dynamic world of technology".

The following partial aspects I will treat in detail: The **historical development** and the close interactions between the development of mankind, technology and materials. The **availability** of materials and its importance with respect to the limited resources. Because of the restricted availability, we are compelled to conserve the limited resources and to handle them as sparingly as possible. That is possible through **recycling**, **optimising** and **new materials**. These current challenges will be treated in view of Honda's philosophy and with the **conclusions** resulting from this.

HISTORICAL DEVELOPMENT

Between man, materials and technology is a steady interaction ongoing for millions of years. The base of progress is an unalterably interconnected three-way relationship as shown schematically in figures 1 and 2 [2].

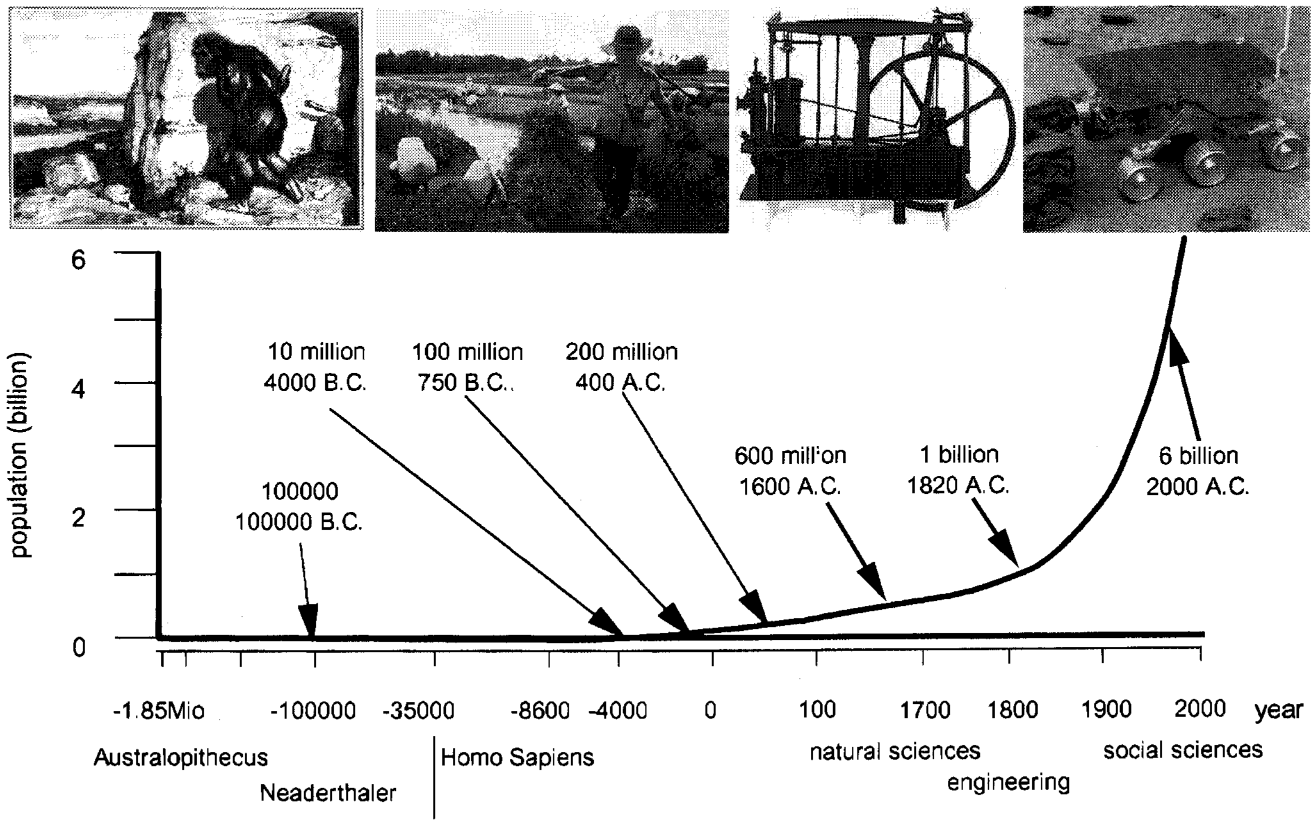

Fig. 1 Evolution of man.

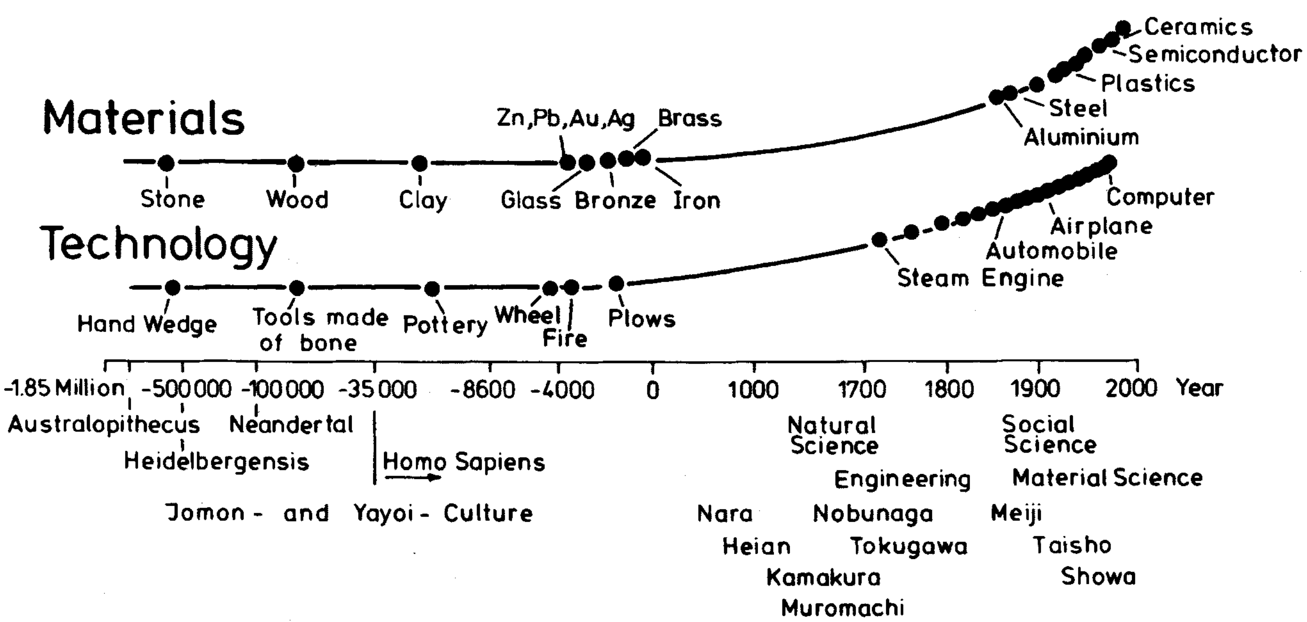

Fig. 2 Evolution of materials and technology.

The earth's population has been continuously multiplying since early man first appeared about two million years BC. E.g. the population grew by a factor of 100 in about 100 000 years, from an estimated 100 000 people to 10 million, and this was reached about 4000 BC. Despite natural catastrophes, plagues and decimating wars, by 1820 the population had grown again by a factor of 100 to 1 billion people, this time in less than 6000 years. Today there are about 6 billion people and the doubling rate is only about 33 years. Accordingly, it could be possible that in not quite 200 years time there will already be 100 billion (10^{11}) people on earth. For the factor of 100 in population increase this period is less than 400 years; compared to 6 000 and 100 000 years the population increase becomes alarming fast.

Of course, all of us are aware, those extrapolations are mostly not reasonable. But no matter whether the steep increase will continue or come into a final state, mankind is faced with drastic increase of population during the upcoming decades.

Overpopulation will more and more influence our life and our thinking.

The four little pictures above in figure 1, express severe changes in the living conditions. Around 4.000 BC when early man settled from a nomadic behaviour as hunters and began with agriculture. And then around the middle of the 18th century: the industrial revolution; symbolised by James Watt's first steam engine. In both cases a change in the habits of living was essential because of the population growth. In both cases materials and technologies have reached a standard, which allows such drastic changes in human being. We are now obviously in the beginning of a third renovation based on the high technological standards available today and symbolised by the Sojourner of the successful Mars-mission. And there is no doubt that this renovation must imperatively enclose the ecological renewal.

In figure 2 the evolution curves of materials and technology are plotted. The rise of the evolutionary curves includes the number of discoveries and technological events; by far not all are mentioned here for reasons of clarity.

As we have learned at school already: Materials are one of our oldest cultural assets. Historical eras are named after the materials that dominated at that time: the Stone Age, the Copper and the Bronze Age and the Iron Age, possibly the end of which we are living through at this time. New materials such as plastics, semi- and superconductors, advanced alloys and ceramics etc. are appearing on the scene and providing an impetus for technological developments, often with far-reaching consequences as is the case for automobiles, airplanes and computers for instance.

In the interaction with materials and technology man is the decisive partner, of course. Materials and technologies are ambivalent. They are, a priori, neither good nor bad. Only man decides about their applications and consumption.

AVAILABILITY OF MATERIALS

Today there is a broad spectrum of materials available, as schematically expressed in figure 3. Besides the natural materials, like wood, sand etc. there is a wide range of engineered materials subdivided in metals, inorganic non-metals, and polymers. All of them have subclasses as steels, ceramics and so on. Composite materials, often very sophisticated combinations of different materials, are gaining more and more relevance for special applications.
Just counting the materials which have been stored in databanks, millions of different materials are already in application. This may seem to be a large number, but the number of unrecorded materials is by far greater, as will be shown later.

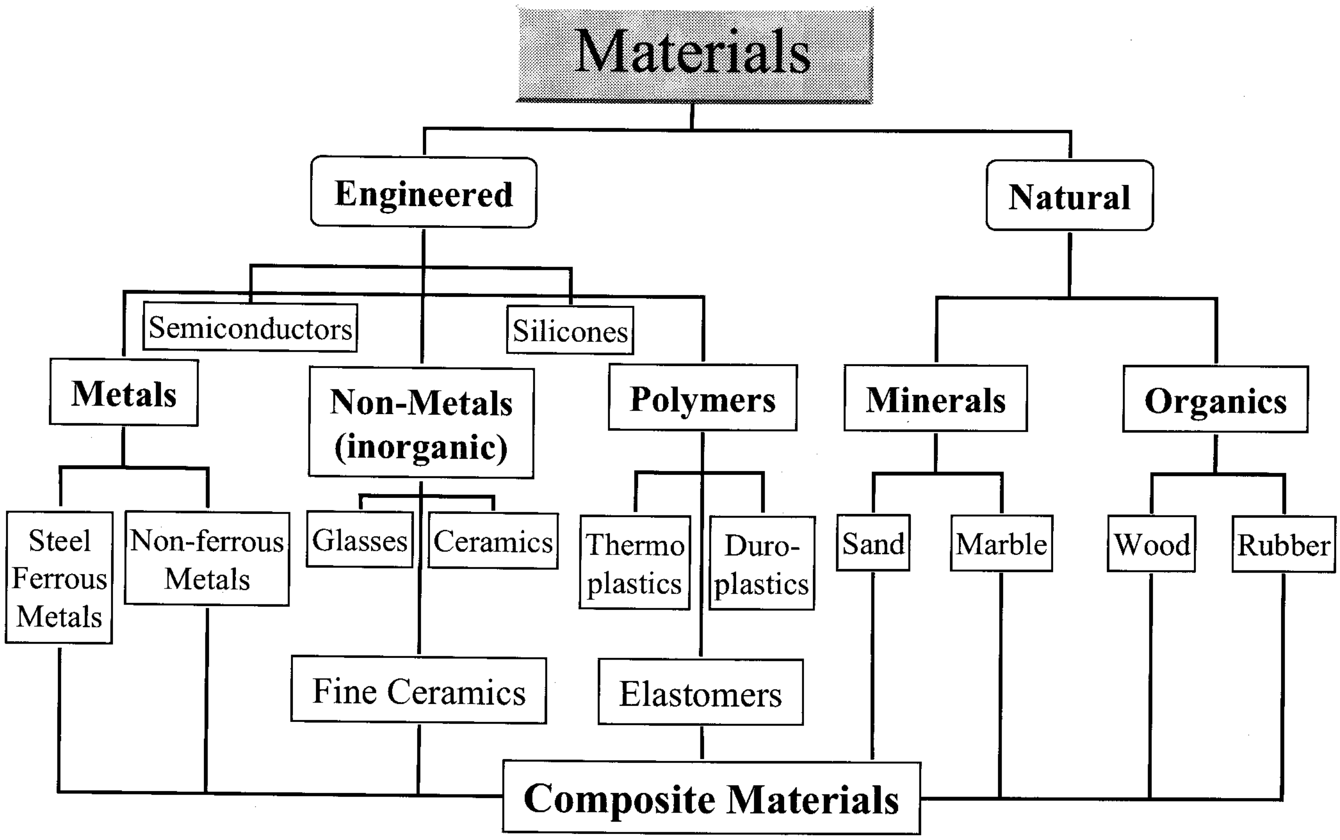

Fig. 3 Classification of available materials.

Although materials are prerequisites for technology and human life; even today materials are mostly taken for granted - they are self evident to most people. Without materials human beings immediately would fall in great trouble and the statement by Georgius Agricola, given about 500 years ago, would become true. He wrote [3]:

"... If mankind ceased to use metals, all the possibilities to guard and preserve health, as well as to lead a life corresponding to our cultural values would be taken away. People would lead the most detestable and most miserable life among wild animals ..."

Everything said about metals can be generalised to all materials. Agricola addressed the social aspects of materials: problems of public health and culture as well as general questions of standards of living. He made the connection between materials, technology and society in context of his time. A time when the unification in Japan by Oda Nobunaga and Toyotomi Hideyoshi took place and on the other side of our globe Columbus sailed to India and discovered America. In our days, the increasing need for materials is obvious. The increase of consumption for all materials is about 15 % in ten years according to a very rough estimate. The largest parts are with the metals, although their consumption decreases for the benefit of the polymers.

The steep increase in materials consumption is caused not only by the fast growing of population but also by higher demands of people (two cars instead of one, ten shirts instead of two, etc.). The increase in the consumption would be very good to improve our economies but at the same time imposes a heavy burden on our anyhow limited resources. And indeed the growing demand of materials implies the "looting" of our planet on non-renewable sources. This becomes directly evident by the fact, that the lasting periods are very short, alarming short for many metals, e.g. for lead only 23 years, 35 for copper, 40 for nickel, to mention just a few [4]. These data reflect the situation of a somehow constant production rate as for the last year. If China or India would reach the same standard of living as the industrial world, the decrease in resources would be much more drastic.

Our evolution has taken a long time to reach the current rate. But today the question arises, whether the steeply increasing population curve and the pace of technological innovations really present true progress! Our earth, often compared with a spaceship (figure 4), has limited resources and as a consequence its loading capacity is limited. The "spaceship" earth as an economic system with limited resources and increasing population is confronted with serious problems. In this universal consideration, the planet earth is a part that may give up energy to its surroundings, but can replace it again from outside, from the sun. Presently this seems somehow futuristic, but solar technique develops quite well. So it might be expected in the not too far future that the energy losses can be balanced at least partially, as shown schematically in figure 4.

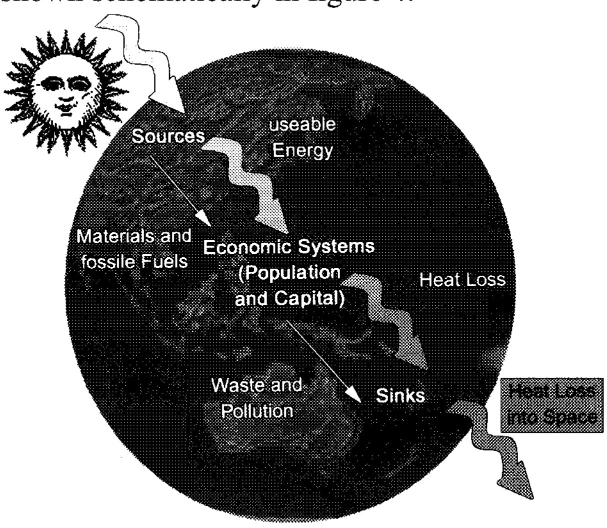

Fig. 4 Global Ecosystem "Spaceship Earth".

But it is totally another matter for material converted by the economy. Out of raw products arise commodities. The consumption of materials out of the concentrated storage places into scattering by mass production and to refuse dumps is regarded as an increase of irreversible loss. Those irreversible losses are unavoidable.

A measure for irreversibility is the so-called entropy, which is defined in the second fundamental law of thermodynamics. According to Albert Einstein the entropy law is the most important law in science.

The entropy law expresses in simple words:

- One cannot break even. (This law gave much burden to Soichiro Honda, because its consequence is that the efficiency of engines are much lower than 100 % (no perpetuum mobile).

The material entropy in the global ecosystem of the world causes an increase in irreversibility. The potential of materials decreases as they are used technically although they do not disappear. They go from a certain concentration to an even distribution [5, 6].

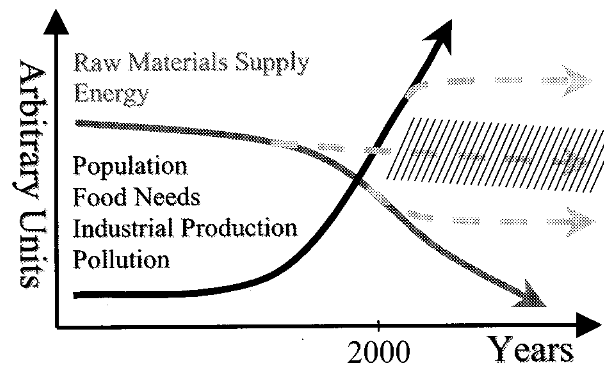

Fig. 5 Change of situation in "Spaceship Earth" (schematically).

As schematically expressed in figure 5, the increase of population would cause a need for more food, more industrial production, more energy and raw materials and as a consequence an increase of pollution. All that yields to an unbalanced situation on earth in the next future, with catastrophic consequences being very likely.

There is only hope for avoiding such a situation by achieving a quasi steady state on our planet by further improving the ecological balance. That means both curves should approach to a course close to a horizontal line. This could be a remarkable contribution to the ecological renewal, which will more and more influence our life and our thinking.

So far as materials are concerned, three directions are important for approaching the steady state on earth:
Recycling - Optimising - New materials.

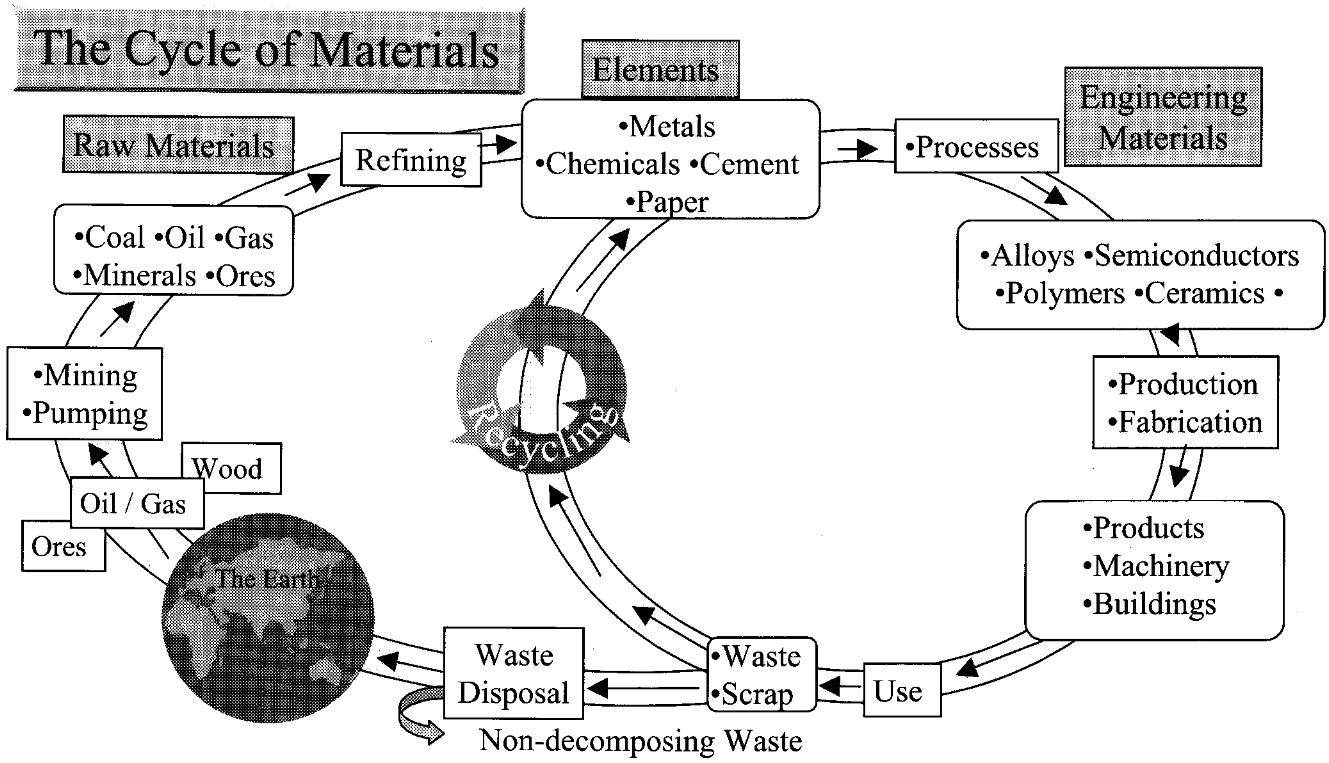

Fig. 6 Cycle of materials.

RECYCLING OF MATERIALS

Fortunately, consumption of materials does not have to be synonymous with a complete irrecoverable loss, but - at least in the most favourable case - must be considered as a stage within the cycle of materials shown schematically in figure 6. The path taken by the substances leads from the resources and raw materials to primary products, declared here as elements, to the engineering materials themselves, which become waste after their use in products of various technological areas [7].

At best, the waste products can be recycled. In less favourable cases they have to be stored in refuse dumps. But even those waste products, not suitable for reuse, are not lost from this cycle, unless they cannot be decomposed by chemical processes or micro-organisms and thus cannot be fed back as resources. Even waste must be considered as a product that cannot simply be thrown away but must be utilised to stretch the available resources.

Many successful examples support this point. This might be underlined by figure 7 showing the recycling rates for some important classes of materials [4]. The recycling rates of iron and steel are encouraging; but with plastics are still problems. But nevertheless the values achieved are a beginning and will certainly be improved in the near future.

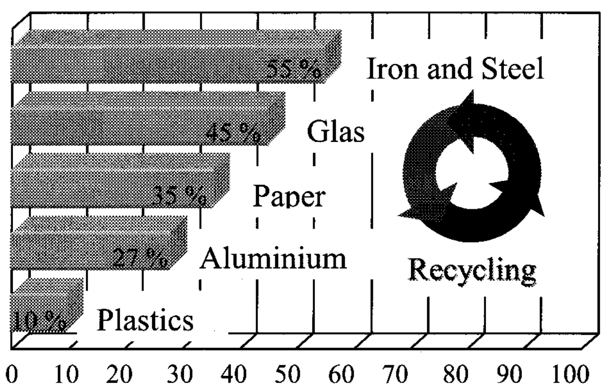

Fig. 7 Recycling rates of several materials.

Non-renewable resources must be recycled if the industrial society wants to retain its standard of living at roughly the same level. However, a complete recovery cannot be achieved as the second law of thermodynamics demands a tribute in the form of entropy.

OPTIMISING OF MATERIALS

Another important approach for saving materials and to stretch the available resources is optimising. Optimising the properties for specific use. E.g.: Improve strength, or conductivity, or duration of life, or reduce weight, or corrosion sensitiveness to mention just a few examples for materials optimising which is saving materials. Since all properties depend on the internal "architecture" of the material an optimising necessitates changes directed to this internal architecture. As can be seen from figure 8 the internal architecture of materials is determined by a whole range of characteristics which extend across a very wide range, from atomic dimensions in the tenth of a nanometer range to the dimensions of structures in the centimetre or meter range [8]. All of the characteristics in this range of scale of several magnitudes contribute, in their own particular way, to the characteristic profile of a given material. In addition to the crystal structure, determined by the interaction of the various types of atomic bonding, the microstructure of a material also plays a significant role in determining its characteristic properties, from nano- to macrostructures of a component, here as an example a turbocharger rotor.

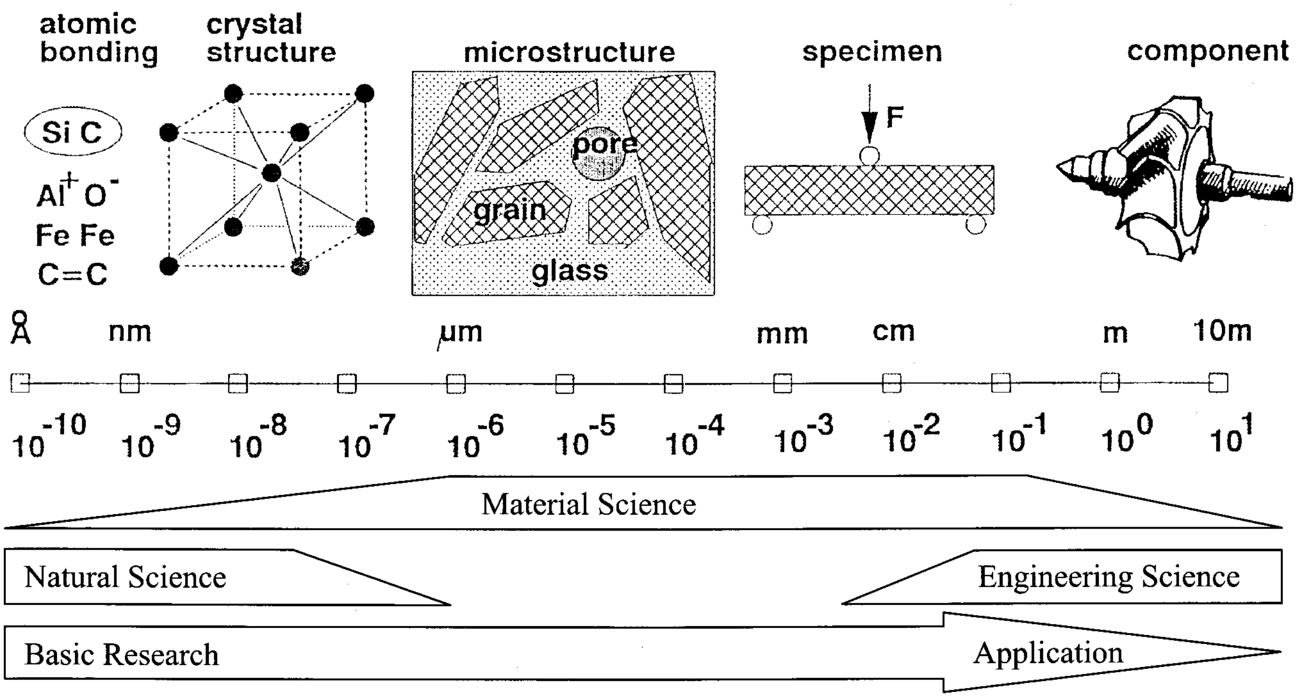

Fig. 8 Microstructural characteristics ranging from the atomic to component size.

The microstructure is an important domain within the science of materials. More and more often it bridges the gaps in communication between scientists on one side, who seldom enough venture outside their field of basic research, and engineers on the other side, who show little interest in leaving their safe macroscopic ground of their continuum conception. The great significance of materials science in technological progress is that it can lead to a basic understanding of internal structure, so that new materials can be invented and tailor-made for specific applications, literally by microstructural and molecular design. Even though materials are an ancient cultural inheritance of man, their scientific exploitation began only at the beginning of this century. Today we know that the internal architecture of a material is determined by the type of atoms it contains and their three dimensional arrangement in accordance with certain degrees of order: from strictly ordered arrangements, such as in crystals, to extremely disordered or chaotic arrangements such as occur in some solidified melts, for instance glass.

Better than words a few micrographs will illustrate a bit of the internal architecture of materials. In figure 9 an example of a material with a relatively high atomic order, a section from a copper single crystal is shown [9]. The copper atoms are arranged in the cubic face centered structure. Each light coloured fleck is produced by a whole column of atoms. The image was produced by transmission of a nanometer thick single crystal copper foil in a high resolution high voltage electron microscope. The direct resolution of this instrument is 0.105 nm, which is less than the distance between the adjacent copper atoms and can thus be resolved. The enormous power of this microscope is demonstrated best by comparison with the human eye. Were our own eyes to have the same ability, we would be able to see a tennis ball on the surface of the moon.

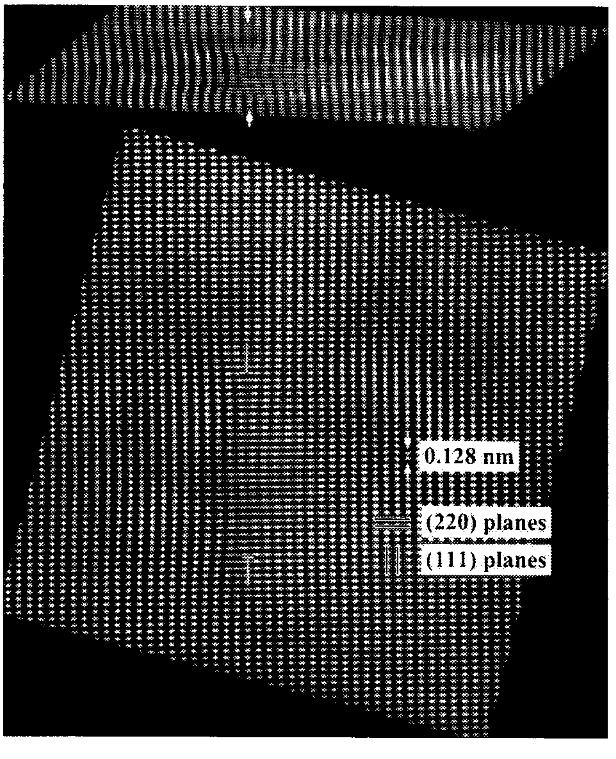

Fig. 9 Direct image of atomic arrangement in a copper single crystal.

In the arrangements of copper atoms some irregularities are to be recognised as deviations from the ideal structure (marked ⊥). Those deviations, called dislocations, cause a certain stress field, which can strongly influence properties like mechanical strength and electrical conductivity. (For instance only one missing atom among 1000 others causes a measurable effect). The change in properties depends strongly on the amount and distribution of those deviations from the ordered structure. There are deviations of several types, which I will not explain here.

Moving from nanometer to micrometer region microstructures like this presented in figure 10 are typical. It's a scanning electron micrograph of a polycrystalline zirconia, which is an advanced ceramic with special strength and conducting properties. There are homogeneous grains and grain boundaries. The facets are caused by the crystal structure. The properties depend on grain size and grain size distribution. With this resolution we cannot recognise lattice deviations like dislocations as in the atomic resolution picture before.

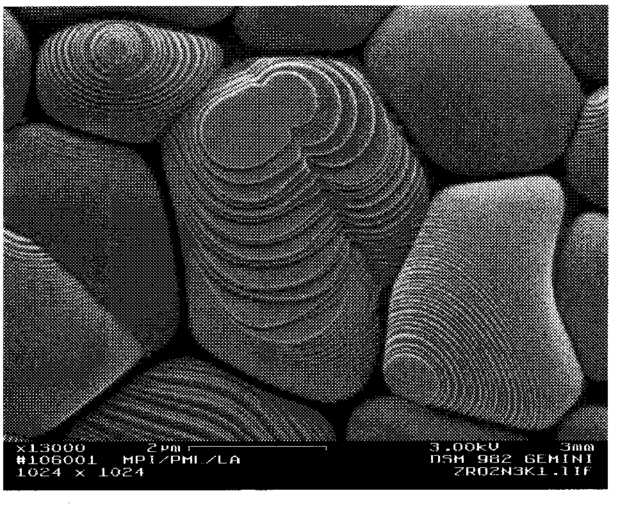

Fig. 10 Scanning electron micrograph of polycrystalline zirconia.

In general: The microstructure can be strongly influenced by external parameters, e.g. stress, temperature, pressure, processing route etc. This should be explained by figure 11 as an example. Scanning electron micrographs are shown of the microstructure of an alumina-zirconia alloy, a well-known cutting tool material. Both samples have the same composition.

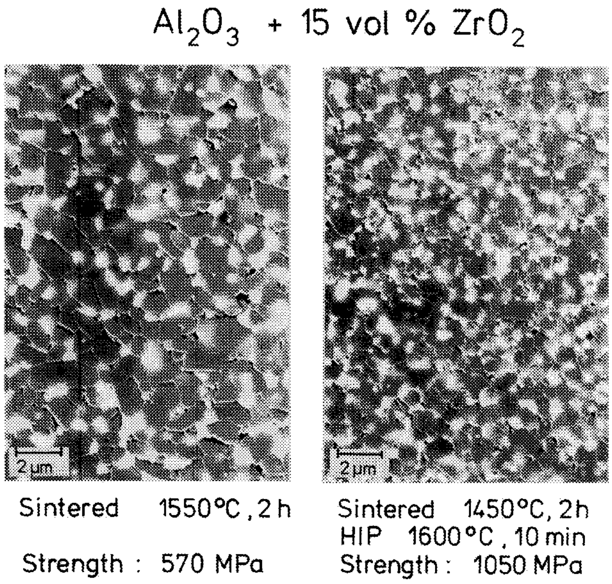

Fig. 11 Example of a microstructural optimisation of a dispersion-strengthened alumina-zirconia ceramic.

The light particles are zirconia inclusions in the alumina matrix, which appears grey. Both samples were prepared by densification of the same starting material. However, different densification processes were used. Although the treatments applied did not differ greatly, a large difference in strength resulted - nearly a factor of two. The reason for this is a minute variation in the microstructure. The treatment of the sample shown on the left resulted in a more pronounced grain growth, and as a direct consequence of the microstructural coarsening, the strength decreased markedly.

Figure 12 demonstrates the relations between a component -in this case a ceramic valve- and its microstructure. The valves are made from silicon nitride and some alumina-yttria additives. Presently there is a test run of about 2000 cars equipped with these valves. Compared to metallic valves they have several ecological advantages: they are lighter (two thirds) and have better wear behaviour yielding to higher performance, lower fuel consumption and lower exhaust emission and they are made from materials which are available in huge amounts on the earth surface [10].

The microstructure of such a valve shows silicon nitride crystals in a white matrix of the additive mixture (middle of figure 12). This section is superimposed in a photo-montage upon a pile of silicon nitride crystallites to show the three dimensional arrangement of the silicon nitride crystals.

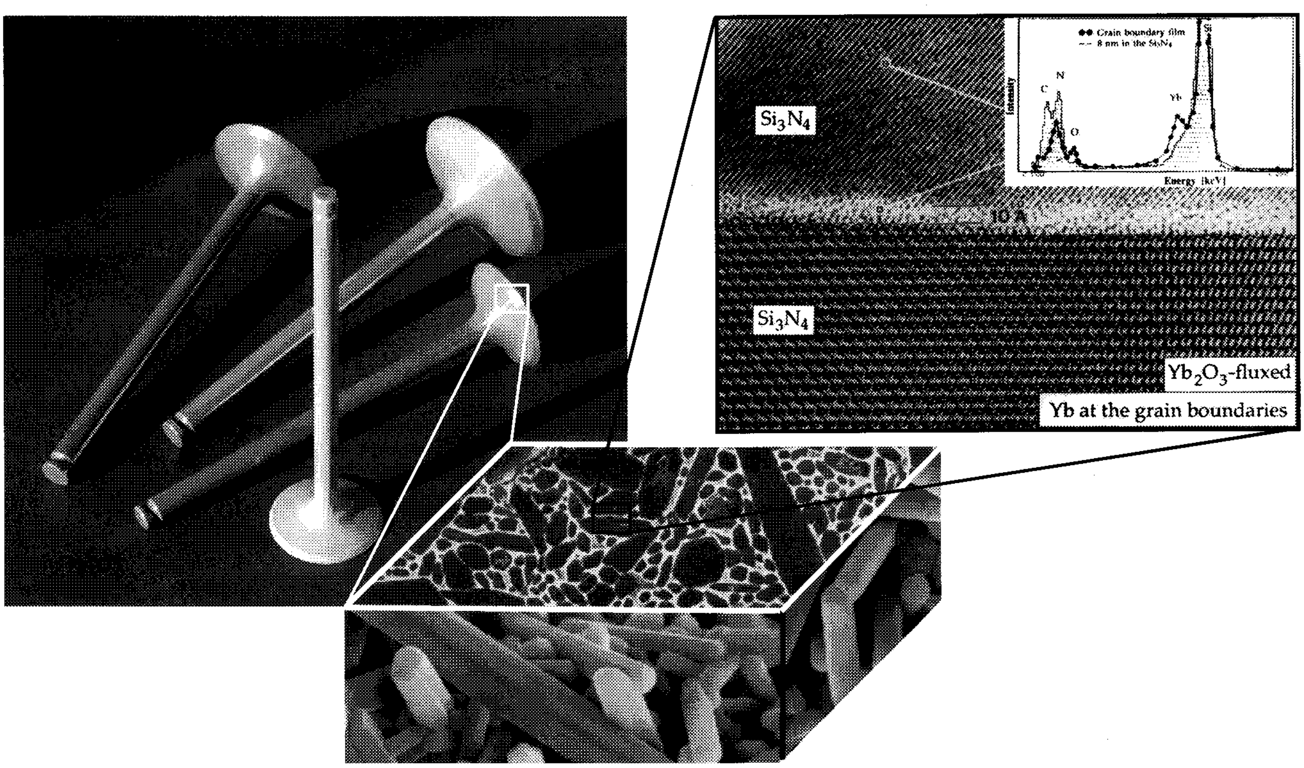

Fig. 12 Macro-micro- and nanostructure of ceramic valves.

A more detailed area of the microstructure gives additional information as to be seen in the right part of figure 12. In the high resolution electron micrograph a direct lattice image of the silicon nitride grains is clearly visible. Between grains there exists only a thin amorphous film, 0.1 nm thick, which markedly differs in its composition from the crystalline areas, as can be seen from the electron energy loss spectrum inserted in the upper right [11]. The ytterbia sintering aid has become concentrated in the amorphous phase. All the information of the macroscopic, microscopic and nanoscopic areas are important for optimising since all the features influence the quality of the component and therefore they have key functions in the development of materials.

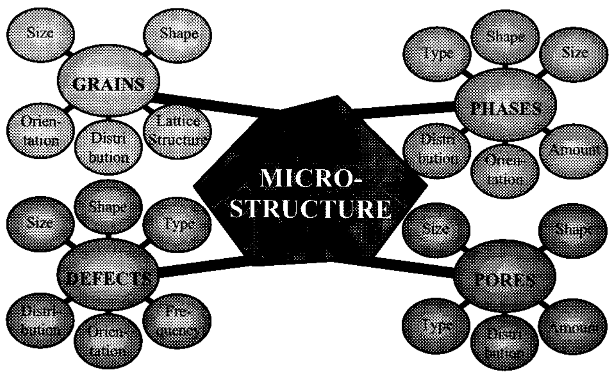

Fig. 13 Different phases and deviations from the ideal atomic arrangements forming the microstructure.

For optimising materials the internal architecture, the microstructure, is a decisive factor. The microstructure is nothing else than the sum of the different phases and the deviations from the ideal atomic arrangements [12]. This is schematically shown in figure 13. Size, shape, distribution, orientation, type, arrangement and amount of the various phases, grains, defects, and pores they all go to form the actual microstructure of the material which thus results from the combination of each of all phases, grains, defects and pores they each contain. Such defects can be from zero to three dimensional, their size reaches from atomic vacancies and dislocations to grain boundaries, pores, and shrinkage cracks. The various different combinations of these factors result in the fascinating multiplicity of possibilities. These microstructural features can exist in sizes spanning more than ten orders of magnitude, as figure 8 expresses. Microstructure can be like a piano on which one can play millions of different melodies.

The microstructural parameters strongly influence many of the properties of a material. Because of this, a great deal of attention is paid to the microstructure in science, development and testing of materials. As a rule, each material contains many million microstructural features in each cubic centimetre. The higher the requirements of a material, the more stringent are the requirements on its microstructure, i.e. the more accurately must its microstructure be established. The aim is to be able to create a microstructure specifically designed to produce a given property profile. The terms "microstructural engineering" and "microstructural design" are the keywords used to describe this process. Optimising of given materials is mainly a steady improvement of properties, a smooth evolution. But real revolutionary surprising steps can be expected only from the invention of new materials, unknown before.

NEW MATERIALS

After all recent developments of new materials, the question as to the potential of further materials arises. Can we hope for significant new contributions, especially if we consider the great multitude of materials already available? The answer is straight-forward: yes!

In fact, potential materials are in abundance and the possibilities of combining and varying elements are almost unlimited even though there are just over 100 elements. The following considerations may help to clarify this: Elements can be mixed or alloyed respectively and combined to systems, the so called phase diagrams, for instance the well-known iron-carbon phase diagram, which includes many carbon steels and cast irons. Phase diagrams are comprehensive descriptions of constitution of matter so far relations between different phases are concerned. The principles of phase equilibria are central to an understanding of many scientific and technological disciplines and are important guidelines in the production, processing and application of materials.

Let us consider 86 of the 100 or so elements we know, and ignore inert gases and the transuranic elements. If we combine these 86 elements to binary, ternary, quaternary phase diagrams and so on, up to the 86-element phase diagram, the total number of possible phase diagram comes to as many as 7.7 x 10^{25}!

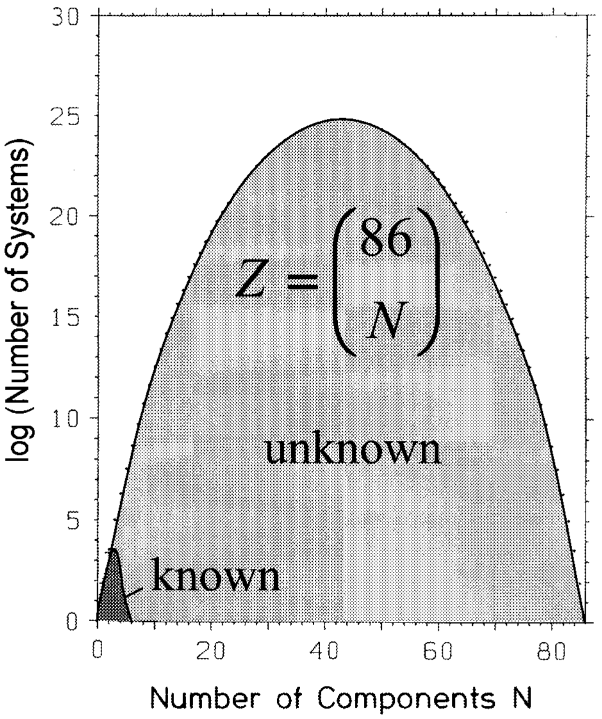

Fig. 14 "Mountain" of Materials.

In figure 14 the number of possible phase diagrams is plotted as a function of the number of elements N. This can be drawn only on a logarithmic scale, otherwise the ordinate would extend to the Milky Way. There are only 86 unary systems (the elements), 3.655 binary systems, more than 100.000 ternary systems and so on and the maximum of 6.6 x 10^{24} phase diagrams is reached with 43 elements. Beyond this maximum the number of possible phase diagrams decreases and finally only 1 phase diagram with all 86 elements exists (which contains all other phase diagrams as subsystems).

On the other hand, the number of phase diagrams investigated decreases steeply as the number of components increases. Altogether about 10.000 phase diagrams are known to date, most of them only partially. This is marked by the small area in the lower left of figure 14. This area represents all known materials. The ratio of known to possible phase diagrams is as small as 10^{-22}. This is not easy to picture and better to illustrate by a comparison. Let us assume the surface of our earth the oceans included would be equivalent to the total number of all possible phase diagrams then the number of the already established would have the size of a stamp.

This "mountain" of materials represents a huge reservoir of new materials. Despite the numerous combinations of elements used in today's materials, a much larger multitude of unknown possibilities remains. Among these could be numerous technological material combinations, which some day could play a role similar in importance as today's steels, superalloys, advanced ceramics and so on.

The dimension of this reservoir increases if one considers that a phase diagram (e. g. iron-carbon) containing many technical alloys is counted only once in this plot. Further multiplication results from the fact that neither modifications (e.g. graphite, diamond and carbon) nor metastable states, e.g. glasses, are included. And even more possibilities arise by variation of the molecular arrangements as in the case of polymer materials. Thus, an incredible abundance of possible materials is a formidable task and nevertheless a great challenge for the materials science community.

However, many of the possible element combinations will be without practical significance. But likewise, many element combinations will result in new engineering materials. In particular, combinations of light elements such as silicon, aluminium, carbon, oxygen and nitrogen, that are abundant in the earth's crust, are of special economic and ecological significance. Research on that is likewise not expensive but not very spectacular and therefore of minor interest to politicians. I think the situation is somehow curious: we are able today to bring little vehicles to the Mars but have only a narrow insight to our materials on earth.

Of course it is impossible to investigate all the phase diagrams experimentally . It would be too time and materials consuming. Therefore one prerequisite for the utilisation of the "mountain" of materials is presented by the computer-aided study of multi-elemental material phase diagrams, a method which has already been developed to a high standard. Relatively few experiments are then sufficient to verify these phase diagrams. The computer software employed is already in use and is an important tool for the understanding of multi-elemental materials and their complex phase equilibria [13]. Although the determination of phase diagrams still relies upon experiments and estimations more and more important information comes from computational thermodynamics (figure 15).

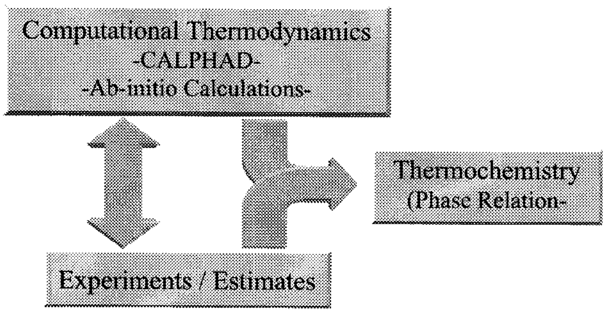

Fig. 15 Determination of phase relationships in materials.

Especially the Calphad (calculation of phase diagrams) method is increasingly used. In addition, ab-initio calculations continuously obtain attention. Ab-initio calculations start with atomistic data, first principles. The dream is to get phase diagrams by ab-initio calculations. Although this is possible in principle, at present the reliability of the basic data sets is insufficient.

At present most phase relations are established by an intensive interaction between calphad, experiments and estimations, with remarkable advantages. E.g. about ten to twenty years ago it was necessary to investigate 300 to 500 specimens to establish a complex ternary phase diagram experimentally. Nowadays by using the interaction between calphad and experiments 10 to 20 specimens are sufficient.

In recent years there have been many technological breakthroughs via new materials. Those materials have a key position since they enable new technologies, not possible before, because of the lack of proper materials. Figure 16 gives an idea of some recent breakthroughs in the development of high temperature materials. This development is a typical example for real progress with striking influence on the ecological behaviour. It is plotted the development of high-temperature materials, the surface temperature against the initial use. It is nicely to be seen the smooth evolutionary development of specific materials, mostly by microstructural optimising and the revolutionary steps with new materials.

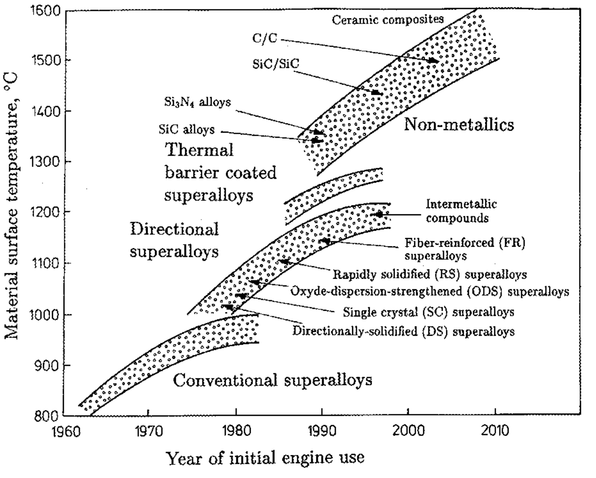

Fig. 16 Evolution of high-temperature materials.

Although the new advanced ceramics are not yet completely optimised a new type of materials is upcoming which very likely might take the next step in the impressive development in high-temperature materials. It is the precursor ceramic which are under severe studies now, especially the silicon carbonitrides. So, one can expect another chemical component to become an engineered material.

CONCLUSIONS

There are still many challenges in the field of materials science. In addition to the already known and well approved classes of materials, composite materials, so called intelligent materials, as well as anisotropic materials and those with cellular structure are investigated world-wide to find new materials for new demands in technology. All of these materials have to be synthesised, produced and optimised by mastering the microstructure and phase relations to get the best properties for a special application. The tetrahedron in figure 17 expresses the most important topics in materials science and engineering. The corners, edges, planes and the space of the tetrahedron symbolise combined actions necessary to understand the very complex field of materials.

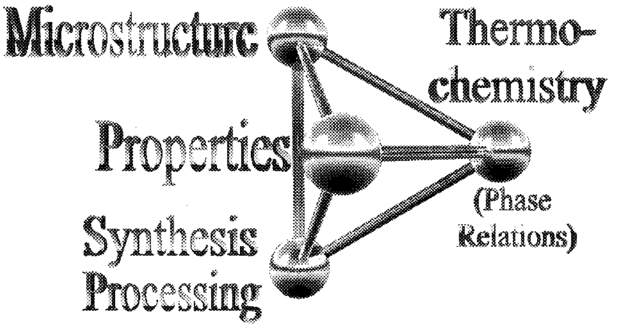

Fig. 17 Tetrahedron expressing important topics in materials science and engineering.

In the beginning of my lecture I have argued that the mankind very likely is after the settlement of hunters to farmers and the industrial revolution now in the beginning of a third renovation: the **ecological renewal**. And again, there is no alternative to technology. Ecology cannot be realised besides technology and not against technology. But there is only one choice for industry and that is to adapt ecologically. New materials and innovative technologies offer a means just for that. There does not seem to exist another solution of our ecological problems than a broadly distributed development of technologies and materials. Materials science can help to ensure that the technological evolution is on the right track: Not only the use of our resources and energies is enhanced, but also our environment is better protected. In short: With less resources, less energy and a smaller environmental impact we must attempt to make today's highest standard of living accessible to all people, based on more intelligent, innovative materials and technologies [14]. In very short: More with less (figure 18). Or just in other words by Soichiro Honda: "There is no limit for the quality" [1].

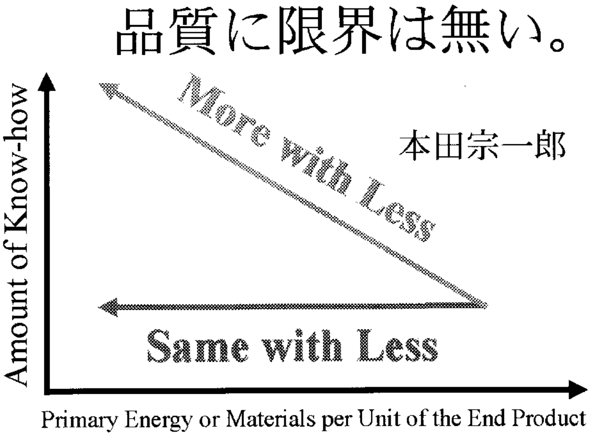

Fig. 18 Aims in Research and Development of Materials.

Based on more intelligent, innovative materials and technologies materials science can contribute significantly to the change in industrial culture. A change that will lead to an ecological future with man in harmony with his materials and his technology. Not a costly program is necessary to reach the goal, but just a co-ordination of special advantages of the partners and in addition some new thinking and adaptation. Or expressed in the simple words of Linus Pauling:

"If man had as much sense as reason, things would be a lot simpler!"

REFERENCES

[1] S. Honda, "Honda über Honda", Seewald Verlag, Stuttgart, 1980.

[2] G. Petzow, "Man, Materials and Technology - Opportunities and Concerns" in High-Tech Ceramics, pp. 1-15, ed. G. Kostorz, Academic Press, London, 1989.

[3] G. Agricola, "De Re Metallica Libri XII", 1556 (revised ed. 1961), pp. 11-12, Deutscher Taschenbuch Verlag, München, 1977.

[4] H. Czichos, "Werkstoffe als Basis industrieller Produkte", Stahl und Eisen, 114 (1994) Nr. 12, pp. 63-70.

[5] Ch. Schütze, "Das Grundgesetz vom Niedergang", Carl Hanser Verlag, München, 1989.

[6] N. Georgescu-Roegen, "The Entropy Law and the Economic Process", Cambridge/Mass. 1971.

[7] H. Czichos, in Atlas Bulletin 5, pp. 20-23, United Nations, New York, 1988.

[8] G. Petzow, F. Mücklich, "Microstructure - Fascinating Variety in Stringent Rules", J. Pract. Metallography, 33, 1996, pp. 64-82.

[9] F. Phillipp, R. Höschen, M. Osaki, G. Möbus, M. Rühle, "A New High-Voltage Atomic Resolution Microscope Approaching 1 Angstroem Point Resolution Installed in Stuttgart", Ultramicroscopy, 56, 1994, 1.

[10] R. Hamminger, J. Heinrich, "Keramische Ventile für Automobilmotoren", Spektrum der Wissenschaften, Jan. 1993, pp. 114-116.

[11] H.J. Kleebe, M.J. Hoffmann, M. Rühle, "Influence of Secondary Phase Chemistry on Grain Boundary Film Thickness in Silicon Nitride", Z. Metallkde., 83, 1992, pp. 610-617.

[12] G. Petzow, "Metallographisches, Keramographisches, Plastographisches Ätzen", 6., überarbeitete Auflage, Gebrüder Bornträger Berlin, Stuttgart, 1994. Japanese Edition through Japan UNI Agency, Inc. Tokyo, 1997.

[13] G. Petzow, E.Th. Henig, U. Kattner, H.L. Lukas, "Der Beitrag thermodynamischer Rechnung zur Konstitutionsforschung", Z. Metallkde., 75, 1984, pp. 3-10.

[14] D. Altenpohl, "Materials in World Perspective", Springer-Verlag, Berlin, Heidelberg, New York, 1980.