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TRENDS IN THE DEVELOPMENT OF ADVANCED METALS WITH REGARD TO ENVIRONMENTAL COMPATIBILITY

PART I: TECHNICAL SOLUTIONS WITH THE AID OF ADVANCED METALS

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For United Nations Industrial Development Organization UNIDO, Vienna
Dept. New Technologies

October 1995

Content

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Introduction

Ozone thinning, the greenhouse effect, global warming, lack of drinking water - these are the alarming keywords which are found all over the world predicting an ecological collapse caused by intensive environmental pollution. The main reason for most of the polluting reagents is the generation of energy and the consumption of natural resources for the different needs of the human race. In most cases energy is generated by firing fossil resources such as oil, coal and natural gases, thus affecting the environment through the emission of gaseous reagents. The energy consume for heating, cooling, transport, industry and the generation of current rises from year to year due to the progressive tendencies in global industrialization, increasing prosperity, and finally due to the exponential growth rate of the human race. Thus the emission of so-called greenhouse gases and aerosols is additionally increased. Table 1 summarizes the main reagents affecting the global climatic situation, their mostly man-made sources and their stability in the atmosphere [1]. Current results of mathematical modelling predict a severe increase of the surface air temperature of up to 2.5°C in the year 2040 based on the effect of both greenhouse gases and aerosols [2]. This must be seen in conjunction with the ongoing thinning of the ozone layer.

However, ecological studies and current activities on the modelling and prediction of global warming and its negative effects lead to industrialized countries calling for a reduction in energy consumption. In the course of industrialization the semi-industrialized countries counteract this positive development by their increasing energy demands, especially for current generation and industry, insisting on the use of their own local fossil energy resources. Nevertheless, at present the industrialized countries are the dominant initiators of air pollution. Figure 1 shows the USA, the former USSR and China at the top of the list of the percentage share in the worldwide emission of greenhouse gases of the different countries [3].

Consumption of fossil energy sources and therefore greenhouse gas emission can be assigned mainly to the four sections heating/cooling, transport, industry, and current generation. In 1991 the total global energy consumption amounted to about 11 billion of coal equivalents [1].

Because of the impossibility of reducing of global energy consumption, the consequence of this environmental situation should be to develop alternative energy resources. Studies by K.-P. Möller [1] show the technical feasability of switching energy-consuming processes to alternative energy sources, avoiding 75% of CO_2 but merely doubling the specific energy price. However, international and intercontinental economic competition makes such a step virtually improbable. Thus, only competition-compatible, conventional technical solutions are practicable which promise a stepwise reduction of the emission of harmful reagents.

2 Fundamentals

Future-orientated solutions to satisfy the demand of mankind for energy are based mainly on the search for alternative energy resources. A lot of investigations are being conducted on energy production through fuel cells or solar-based processes such as photovoltaics, solar plants, solar collectors, etc. By using solar processes or hydroelectric power plants , water is broken down into hydrogen and oxygen to be used as fuel components for thermal engine-driven machines. This reduces greatly the particle and reagents emission. However, this technique necessitates the development of hydrogen storage and adapted motor concepts. A further solution for transportation is the use of electric motors based on future current generation with solar plants or photovoltaics. Also fuel cells, using hydrogen and oxygen as reagents or the Molten Carbonate Fuel Cell (MCFC), are thought to be good candidates for automotive engines. All these developments are medium-term or even long-term solutions and must be carried out with priority. Taking into account the rapid increase in energy and raw materials consumption, caused by the prosperity of the industrialized countries and the increasing industrialization of the developing countries, short-term solutions are necessary. The main demand is the systematic decrease in the consumption of fossile resources and raw materials.

Solutions are fundamentally based on the following technical approaches, mainly driven by the demand for fuel and raw materials saving (fig. 2):

Application-based solutions

- reduction of weight for all kinds of vehicles and for the moving parts of engines
- improvement of the energy efficiency of thermal, engine-driven machines
- Applications based on natural raw materials

Production-process-based solutions

- optimization of the production processes
- Recycling of materials

WEIGHT REDUCTION can be realized by new, light-weight designs in addition to the use of advanced materials such as modified plastics, metal alloys and natural materials such as cotton, coco fiber and natural rubber. The light-weight effect is mainly based on the following materials properties:

- specific weight
- Young´s modulus (stiffness)
- strength

Lower material specific weight will directly reduce the application weight. However, materials with low specific weight but insufficient stiffness and strength only contribute moderately to the reduction of weight. In general, the required application performance limits the admissible elastic deformations caused by operational loads. Thus, the stiffness of the material used must be high enough to meet the tolerances required. Stiffness is the mathematical product of Young´s modulus and the moment of resistance against bending, respectively torsion. As the moments of resistance depend on the part´s dimension, too low a Young´s modulus must be compensated for larger dimensions in order to attain the required stiffness. This means partial or complete compensation of the specific weight-induced light-weight effect. The situation that low-specific weight materials commonly show a low Young´s modulus is the driving force for materials researchers to invent new modified material composites featuring both low specific weight and high stiffness.

High strength at room temperature as well as at elevated temperatures is a requirement for weight-optimized structures. High material strength permits the appropriate reduction of application dimensions. However, many low-specific weight materials, plastics or metal alloys show insufficient strength at low temperatures and severe creep effects under load at elevated temperatures. As a consequence, the reduction of stress by enlargening of the part´s dimensions results in an increase of weight. This fact shows the necessity of developing of new plastics and alloys as well as modifiying of the existing materials with secondary phases in order to improve the material strength corresponding to the operational and weight requirements.

In summary, the results of the above paragraphs, i.e. low material specific weight in combination with both high stiffness and high strength, are necessary to reduce application weight.

Additionally, the weight-saving potential of materials with low specific weight, high stiffness and high strength is limited by the materials´ formability. This leads to critical design limits in forming processes such as casting, forging, milling, etc.. Thus, in order to gain maximum weight saving, two materials development approaches are being pursued:

- the development of new advanced materials or material compounds with low specific weight, high stiffness and high strength
- appropriate processes for optimum formability of the above-mentioned light-weight materials in order to make maximum use of their weight-reduction potential.

Both material cost and process cost must be compatible with the competitive situation.

THE TOTAL EFFICIENCY of thermal, engine-driven systems is based on the efficiency of the thermodynamical process itself and the dissipation of energy caused by friction between articulating machine parts. Thus, the total efficiency can be improved by

- optimizing of the thermodynamic process of the thermal engine
- increasing the admissible rate of revolutions by reducing the weight of oscillating engine parts
- reducing friction between moving parts

This study focuses on the first two topics.

The efficiency of the thermodynamic process is dominated by the level of the entrance temperature of the gaseous medium. Efficiency increases at higher temperatures. Additionally, a higher admissible gas temperature in combustion chambers improves the completeness of the chemical reaction. This leads to an increase in efficiency and consequently to a reduction of pollutants. Depending on the type of thermal engine, temperatures from 600°C up to 1400°C are discussed.

Higher process temperatures require new advanced metal and ceramic materials matching the complex thermal-mechanical load situation. The main demand concerning mechanical properties is an improved resistance to fatigue and creep at elevated temperatures in addition to a sufficient degree of ductility. This postulates a microstructure which is thermodynamically stable at the required temperatures over an economically useful period of time. Depending on the operation environment (corrosive, inert medium, etc.) an additional acceptable resistance of the material to high-temperature corrosion and oxidation is inevitable. Since there is no steady state for microstructure and corrosion, respectively oxidation, at elevated temperatures, intensive efforts are being made to modify materials in order to prolong the period of these changes. Concerning the mechanical properties, optimizing of the material´s chemical composition and solutions based on material composites is being pursued. Corrosion, respectively oxidation behaviour, is improved by defined adaption of the chemical composition or by appliying of protective coatings. However, in most cases the first "intrinsic" solution exhibits contrary effects on mechanical properties and oxidation/corrosion resistance.

The demand for increased rates of revolution for oscillating or rotating engine components leads to the necessity of materials with low specific weight in order to reduce the mass forces. For components used at room temperature and slightly above or below, the technical problem is comparable with that of the above-discussed light-weight structures. However, the combination of low specific weight and high mechanical and thermal loads postulate more advanced materials properties. New materials such as intermetallic alloys are being developed in order to close the gap between standard metal alloys and ceramics for high-temperature, light-weight applications.

OPTIMIZED PRODUCTION PROCESSES are necessary to reduce energy consumption during material and component manufacturing. High-performance computer systems for process control and new processes provide a powerful feature for this objective. Also "old" material-production processes, such as steel production, have to adapt to the new requirements. Process steps like ore drying, coke production, etc. must be dicussed critically. New knowledge in materials science and chemistry offer a baseline for new developments. Investigations on the ecological harmfulness of chemical reagents necessary for materials production lead to a better understanding of the interaction of industry and environment, necessarily bringing about a partial reorientation of the industry.

However, advanced high-performance materials, such as metal/metal and metal/non-metal composites, dispersion-strengthend materials and materials of high purity are based on new, sometimes exotic processes. Increased energy demand and production expenditure must be carefully compared with the predicted technical and environmental benefits of the new material.

RECYCLING is a key target for all standard materials and new advanced materials used in mass production. The main goals are saving the raw materials resources and primary energy for materials production and to reduce waste. The best example is the virtually complete material loop circuit for steels. However, for many materials the main problems are founded on the fact that recycling the same base material but with different chemical additives leads an deterioration of the materials quality. Additionally, research activities over the past years have been based more and more on adapting materials properties to the technical requirements by means of materials composites and compounds. Metal-polymer compounds, for instance, are thought to combine the advantageous properties of both these different materials. However, separating of these different materials for recycling is a severe problem. This shows that the production of tailor-made materials often counteracts recycling requirements.

A new approach to environment compatible materials is the use of natural materials. This concept is commonly named Design for Environment (DFE). Advantage of natural materials is, that they can easily be diposed by emitting exactly that quantity of CO_2 they consumed during growth. Thus ecological balance is guaranteed. Typical representatives of such materials are cotton, coco fiber, natural rubber etc.. They are up to one fifth of the weight of metal or polymere materials. Typical applications are automotive parts such as door covers, head restraints and insulating parts. Even composite materials are thought to be produced by replacing glas fiber by flax fiber in glas fiber reinforced plastics. The future could even be the replacement of oil-based plastics by tree resin.

TO SUMMARIZE the above-mentioned aspects, the complexity but also the potential of material-based solutions for reducing the emission of reagents are obvious. Current research in the field of materials engineering clearly shows the path towards tailor-made materials for the specific operating conditions, applying material composites and compounds. However, in many cases the structure of such tailor-made materials is not completely compatible with the requirements for a recycleable material. Thus, the development f new advanced materials will always featuren the conflict between ecological, economic and technical aspects.

3 Objectives of the Study

In this study a global overview is given of current and future technical research with the aim of reducing the ecological incompatibility of critical technologies such as heating/cooling, current generation, industry, transport. Focussing on the emission of reagents and sparing energy and raw materials, solutions from the materials research point of view are pointed out, referring to the above paragraphs.

With respect to the above paragraphs and the wide field of researches into metal, ceramic and polymer materials, a complete study of new advanced materials and their environmental compatibility must be subdivided into the following seven sections:

Part I: Metal Alloys

Part II: Ceramic Materials

Part III: Polymeres

Part IV: Natural Materials

Part V: Production Processes

Part VI: Recycling

Part VII: Global View on Life Cycle Pollution

In the following Part I of the study, tendencies concerning metal-based solutions for light-weight structures and the increased efficiency of thermal engines are indicated. The resultant development of new or modified metal alloys is described and discussed. These results provide the necessary baseline for the further parts of the study and for the last and most important part, the global view of the life cycle pollution of new materials-based solutions. This comprises an estimation of the total consumed energy and emitted harmful reagents of a technical component, including raw material production, transport, processing, recycling and/or waste disposal. Only in the context of this final global view can the real degree of benefit of new materials solutions for the reduction of environmental pollution be defined within statistical limits.

4 Tendencies in Technical Solutions f or Ecological Compatibility

4.1. Light-weight structures

4.1.1. Ground transportation systems

In ground transportation systems (cars, trains and trucks), weight reduction is one of the most important research fields. Reduced structural weight is necessary to just keep the level of fuel consumption constant because of the weight-intensive security devices such as airbags, ABS and so on. In trains, the requirements for comfort (airconditioning, kitchen) are weight-intensive but necessary components of modern train systems. Trucks virtually need to have a low structural weight, as they must carry as much freight as possible.

General Aspects of Light-Weight Construction in Ground Transportation Systems

Weight saving is (in most cases) an expensive thing. Often it is necessary to use new machining and joining technologies. Further, every material has its own "rules of construction" which have to be learned. All these things are expensive and risky, especially in public transportation systems - and thererfore new light-weight constructions will be established only when there is a significant marketing advantage. This advantage could be an improved environmetally benign product. In the European automotive industry an additional expense of 6-8 U.S.$/kg weight reduction is accepted due to the fact that 100 kg weight reduction effects 0.3 - 0.6 l/100km fuel saving.

There are different philosophies in light-weight construction. The first and apparently easiest method is to optimize the conventional steel construction principles. The use of high-strength steels, bake-hardening steels, tailored blanks, and laser-beam welding technologies will allow saving about 20 kg in a car body of 400 kg raw weight. The weight reduction increases with the amount of light metals. A pure aluminium car (same raw body weight) will be about 130 kg lighter than a conventional steel body - but nearly 40 % more expensive, see fig. 3 [4]. For example, the new BMW 5 series is equipped with an aluminium chassis, the rest of the structure consists of conventional steel. The automotive and especially the commercial vehicle market is very sensitive to the cost/benefit ratio [4]. The tranportation industry (trains and trucks) is very interested in low operating costs because of the long distances that goods have to be carried in modern times. Although fuel consumption is only one part of the operating costs it is still a big one - and in future the fuel price may increase because of new, environmentally benign tax systems. At the moment discussions are under way in the European Union to increase the taxes for environment-polluting products such as fuel or some chloride-based chemical products. From this point of view it is a necessity for the industry to develop products featuring low energy consumption. Some politicians in Germany demand a fuel price of 3,30 U.S. $/l (exchange rate: 1$ = 1,50 DM) in the year 2005. Today we have a price of 1 US$/l. If only half this demand is be followed, we will have a fundamentally new situation in the European industry.

Today there are developments in progress in all parts of the transportation system industry to obtain competitive products for the next millennium. For example, AEG has developed a new locomotive containing high amounts of plastics and light metals in combination with a new aerodynamic design [5]. An example of light-weight lorry construction concepts can be seen in (fig. 4 [5]). In future many parts of both street and rail-guided systems will be based on light metal and plastic materials.

Ground transportation systems - Materials Overview

The major light-weight materials used for automotive and train applications are aluminium and magnesium alloys. At the moment (1995) interest in magnesium is increasing, although in the past quite a lot of magnesium was even used, especially in automotive systems. Because of this fact, the emphasis of this part of the study focusses on the basic magnesium technology and the major differences between magnesium and aluminium in terms of fundamental technological properties. An overview of aluminium technology is given in the section "Aerospace Technology: Materials Overview".

MAGNESIUM for automotive mass-production was first introduced in the Volkswagen "Beetle" in 1936. It contained more than 18 kg of magnesium when it went into production after World War II. The main reason for the extensive use of magnesium in those times was the remaining stock of magnesium from war plane production. At the end of Beetle production in 1980, the entire amount of magnesium used was about 345.000 t [6]. Magnesium offers a whole number of advantages for the automotive industrie.

- Highly developed technical processes
- High castability
- Nearly unlimited resources (seawater)
- Stable prices
- Not traded on the commodity exchange

Magnesium with a specific weight of ρ=1,7 g/cm^3 offers a very high structural efficiency.

This means the ratio between the load it can support and its weight. It is defined as P/Vρ, where P is the load, V is the volume of the part and ρ is the specific weight of the material. The range of this ratio is shown in fig. 5a [6]. It is obvious to see that magnesium offers competitive properties in comparison with the other materials.

Another important property of an engineering material is its stiffness. The stiffness is relating to the elastic deflection of a part (for example a beam) under load. The higher the stiffness, the lower is the deflection. The values for Young's modulus are given in fig. 5b [6] for the most important structural materials. At first glance it seems that magnesium has the lowest stiffness of all the metals. But from the point of view of light-weight construction, the ratio between stiffness and weight is of greater interest (fig. 5c). With regard to strenght, magnesium offers

- Nearly the same stiffness / weight ratio as
- Higher strength / weight ratio

than aluminium and steel.

The major problems in the usage of magnesium are its about two times higher price compared to aluminium and from the technical point of view the contact corrosion. Magnesium exhibits contact corrosion to every other metal of engineering interest. This matter has to be considered in every construction containing magnesium. Furtheron, exposing magnesium to elevated temperatures in the range of 120°C and higher effects creep problems.

In recent years many classical steel products in the automotive industry have been replaced by magnesium because of its high-strength/weight ratio and its good castability. For example, alloy AM60 replaces steel in a van seat component. The reduction of weight in this special application is from 4kg (steel component) to 1kg (magnesium component). The part is, like nearly all magnesium parts, die-cast. Alloy AM 60 is also used for instrument panels and steering wheel armatures. The material satisfies all functional and crash-energy management requirements because of its toughness and high elongation. A new alloy development is the alloy AE42. This alloy contains 2% rare earth metals and has a high creep resistance. Its operating temperature up to 175 °C (the maximum for AM and AZ alloys is 135 °C) makes it very interesting for light-weight drive-train applications. Although not yet qualified, the material is being considered for applications such as automatic transmission housings [7].

All current magnesium applications at the big automakers are die castings. Some applications in die-cast magnesium are shown in fig. 6 [8]. Because of the relatively large investment necessary for production dies, much of the preliminary design and test work is often done using plaster - or sand-cast prototypes [6].

ALUMINIUM and magnesium technology meet at this point. Many structural parts made of magnesium were constructed as aluminium parts and then - depending on the actual cost ratio between aluminium and magnesium raw material - die-cast in the same dies with the cheaper material. Therefore a magnesium-optimized construction to take advantage of the excellent properties (castable to thinner wall thickness than aluminium) is often not possible. In past years, aluminium often won the cost competition. Aluminium has many advantages for structural applications. Its high availability in combination with low and relatively stable prices makes aluminium a very interesting engineering material. Aluminium offers high stiffness, low weight (ρ=2,7 g /cm^3) and good castability. In contrast to magnesium, the shavings of aluminium are virtually inflammable. The corrosion resistance of aluminium is in the order of magnitude of magnesium, but it has a smaller tendency to galvanic corrosion. The main poblem in magnesium is often its poor creep resistance. At elevated temperatures (>120 °C) aluminium is often the better choice.

From the recycling point of view it has to be considered that aluminium alloys are divided into two basic alloy types: The wrought alloys and the cast alloys (magnesium cast and wrought alloys are also subdivided - but magnesium is only used in the automotive industry as a casting alloy). The problem is that in the recycling process of aluminium (melting of scrap metal), a casting alloy - which often contains high amounts of silicon and copper - does not have to be mixed with a wrought alloy. When such mixing happens, the result is an alloy with poor castability and - as a wrought product - with low strength and ductility [9]. Sometimes the combination of cast and wrought alloys in the same product is of great advantage and then the mechanical engineering demands counteract the recycling point of view. In spaceframe structures for cars, the combination of extruded profiles with cast knots is the preferred solution. The necessity to take apart the knots and the rest of the structure makes the recycling process expensive.

4.1.2. Aerospace Applications

General Overview

For aircraft, light-weight construction is a fundamental assumption to guarantee the function and the economic efficiency of an aeroplane. Every kg of weight reduction increases the payload and decreases the fuel consumption. In contrast to the situation on the automotive market, the accepted cost-increasing per kg weight reduction for aeroplane applications is about 600 - 800 U.S.$ [10]. Further, the production period of a type of aircraft is significantly longer than that of automotive systems. An aircraft type will be produced over a period of 15 and more years. The development costs must be regained in this time.

In aerospace construction, not only the weight is a matter of interest. The fatigue behaviour and the strength-to-weight ratio play an important role in the selection of materials. Therefore the major alloy systems for structural application are not aluminium and magnesium cast alloys, as for trains and street-guided transportion systems, but aluminium wrought alloys and titanium-based alloys. These alloys, based on the AlMg-system (2xxx) and AlZn-system (7xxx) and TiAlV alloys offer the best compromise between all the requirements of aerospace engineering.

A study by Lockheed Ind., although written for a military plane, is of general interest [11]. It says that if weight is to reduced by 10%, the density must also be reduced by 10%. In this case the strength has to be increased by 35%, the stiffness by 50% and the fatigue tolerance indeed by 100%. This strongly underlines the position of light-weight metals in aerospace applications. Aluminium is - because of its lower price - always the first choice. Only when special demands (corrosion resistance, strength or creep resistance) require special properties, is expensive titanium used [10].

Aerospace Applications - Materials Overview

The question for the aerospace engineer is to find the best compromise between cost, safety and weight (fig. 7). In the next paragraph of the study, a general overview about the most important development approaches and a short description of the "state of the art" will be provided.

In past years the content of light metals, especially of aluminium, has decreased in aeroplanes. The reason is simple: The development of advanced plastics. Fig. 8 [12] shows the increase of the content of plastic-composite materials and the decrease of aluminium from more than 70% (A300) to about 65% in the new Airbus A340. On the other hand, the content of new Al alloys in the planned Airbus 2000 will be about 10-15%. These new alloys such as AlLi or AlMgSc must be discovered or developed over the next 5-10 years.

In 1994 Alcoa developed a new AlLi alloy with reduced specific weight due to lithium. It features a 200% higher fatigue-crack-growth resistance than AA7075-T651 (AlZn-based and heat treated). It is also reported to have 35 % higher fracture toughness than AA7075. A potential application for this new alloy might be the vertical stabilizer and tailplanes for the Boeing 777 or Airbus 330/340. Investigations on the resultant weight reduction show that, using the new alloy, weight savings of about 12% could be realized fpr the above-mentioned parts (related to conventional aluminium alloy). The cost per kg weight reduction is 480 U.S.$ [13] and therefore in an acceptable range.

Table 2 [12] shows the typical application fields for the two major aluminium alloy groups 2xxx and 7xxx. Metals are always the first choice when excellent fatigue resistance in combination with high ductility are needed to fulfill the safety requirements. Especially the alloy series 2xxx, based on the AlCuMg-system, is known to be very damage-tolerant. Therefore one of the main application fields for this alloy type is sheets for the outer skin. The high-strength alloys of the 7xxx series are often used for forged parts and extruded sections. Typical properties of the 7xxx-series alloys are given in Table 3. Although there are corrosion problems in ground transportation systems as well the requirements for aerospace materials are much higher. Therefore many of the alloys used in aeroplanes must be of high purity to secure minimum stress crack corrosion sensitivity.

Today, and probably in future, the development of aluminium alloys plays and will continue to play an important role in materials research. For example, in past years a new alloy - AA6013 (AlMgSiCu) - has been developed and is under practical examination. Its major benefit is good weldability and lower cost in contrast to AA2024 (AlCuMg) [12].

Because of the high stiffness demands in aerospace applications, reinforced metals (MMC - Metal Matrix Composite) have been developed. The reinforcement usually consists of high-modulus ceramics like silicon carbide (SiC) or alumina (Al_2O_3) in long-fibre, short-fibre or particulate form [14]. Usually aluminium and titanium are used as the matrix material. In future, the particulate and long-fibre reinforcement of magnesium alloys will be of increasing interest. Other forms of reinforcement such as whiskers are of little interest only. Whiskers are said to cause cancer, and the benfit of the properties of the composite is relatively low compared to the other reinforcement materials.

The main effect of the reinforcement is an increased Young's modulus and therefore a higher stiffness of the material. The maximum tensile strength does not increase by particulate-reinforcement, although the strain-hardening rate and the yield strength will increase. This effect is called the stain-hardening effect and is based on the increasing internal stress caused by dislocation movement. In reinforced metal matrices, the dislocations cluster at the particles or fibre boundaries and strengthen the material.

One problem in all reinforcement technologies is the significant decrease in ductility and fracture toughness, caused by the above-mentioned effect. The damage tolerance will also decrease. Because of the last-mentionened reasons, the usage of MMC's in aerospace applications as well as in automotive applications did not yet reach the status of serial production. Research on improving ductility and damage tolerance is still in progress. Some applications of SiC long-fibre-reinforced titanium are under development in the United States to improve the propulsion capability of military aircraft, see fig. 9 [15]. The development in continuous-fibre-reinforced aluminium matrices is also continuing. In recent years the company 3M developed an alumina fibre with excellent properties [16]. The composite features a very high Young's modulus in fibre direction and is therefore suited for stiffness- and bending-sensitive applications such as the service panels of an aeroplane, see fig. 10 [16].

Summarizing the above-mentionend aspects, a general catalogue of the properties of new aeroplane materials can be drawn up to include:

- Low density
- High strength
- High fracture toughness

- High stiffness
- High damage tolerance (epecially for the wings)
- Good weldability
- Reproducability of material's properties

None of these requirements can be fulfilled by one material. But not every part has to combine all these properties.

4.2 Efficiency of Thermal Engines

4.2.1 Automotive Engines

Research on automotive engines concerning the efficiency of the thermal engine focuses predominantly on oscillating, light-weight components. Materials with low specific weight but high strength and stiffness allow the reduction of oscillating masses. This results in a higher number of revolutions and therefore a fuel saving, a decrease of reagent emission, and additionally a reduced noise level. Typical oscillating parts are pistons, valves, con rods, etc. However, new materials for this purposes may not or only slightly exceed the component cost of the conventionally manufactured component. Therefore titanium alloys with excellent mechanical properties have not been directed towards light-weight applications in commercial vehicles.

In the past few decades a lot of work has been done on the introduction of special Al alloys to the piston technology of cars and commercial vehicles. Decisive materials properties for Al alloys applicable for pistons are fatigue resistance, form stability (stiffness) and resistance to thermal fatigue in combination with a low coefficient of thermal expansion (CTE). The latter is mainly important for high-performance diesel engines. A typical standard light-weight alloy designed for pistons is the Al-base cast alloy AlSi12CuMgNi. However, the thermo-mechanical loads of high-performance diesel engines with high combustion pressure involve fatigue failure of the material at the rim of the combustion bowl and the piston ring groove. Therfore replacing the material locally at the failing points by alloys with better high-temperature capabilities is necessary. One solution which has already been transferred into the series prodution of trucks is the local reinforcement of the critical points by aluminium matrix composites (MMC) [17] or, as is under investigation, by titanium aluminides (fig. 11). On the other hand, new composite alloys with improved high-temperature properties and additional reduced specific weight are being investigated. Such new alloys produced by the conventional squeeze-casting process are SC-$(Mg_2Si)30Al70$ or SC-$(Mg_2Si)20Mg80$ [18, 19]. These alloys offer mechanical properties comparable to the standard piston Al alloys but with less CTE, higher stiffness and a 10% (Al-base alloy) to 30% (Mg-base alloy) lower mass.

A further potential for fuel saving consists in the reduction of friction in the valve mechanism. Energy loss due to friction is mainly caused by the the valve tappet sliding on the cam of the cam shaft [20]. It is evident that high valve spring forces increase friction between the cam and the valve tappet. As the valve spring force is a function of the moved mass of valve and valve spring (fig. 12, 20) the spring force and thus friction can be drastically reduced by decreasing the mass moved. A reduction of fuel consumption up to 4% in the ECE cycle is achieveable (fig. 13). Fig. 14 shows the light-weight potential of titanium alloys and ceramics compared to the steel version of the valve. From the metals point of view, titanium alloys are hopeful candidates for the less thermally loaded inlet valves. For exhaust valves working in the temperature range of 700°C to 900°C, the intermetallic NiAl alloy is a possible material solution due to ist superior oxidation resistance. Whether ceramics or titanium or alumindes are used for valves in automotive engines in future depends in the final resort on the manufacturing costs and the reliability. As mentioned above, the valve spring mass also contributes up to 50% to the moved masses in the valve system. With the use of a cold-formable and age-hardenable beta titanium alloy Ti13V11Cr3Al, mass can be drastically reduced by 130% compared to the steel version at the same load level. Additionally, the natural frequency and thus the possible operational frequency is increased by up to 50% [20].

The development and application of high-temperature metal alloys is limited to some few motor components such as catalysts or the combustion areas of high-performance diesel engines. Direct injection systems as have been introduced to reduce fuel consumption and particle emission require high-temperature metal alloys. The main demands are excellent resistance to high-temperature corrosion and high strength at temperatures up to 1300°C [21]. As ferritic Fe-base oxide-dispersion-strengthened (ODS) alloys can be treated by conventional production processes, they are privileged candidates for use in the pre-chamber of diesel engines. A typical ferritic ODS alloy is Incoloy MA 956 (Fe20Cr4,5Al0,5%Ti + Y_2O_3 dispersoids).

4.2.2 Industrial Gas Turbines and Aero-engines

Gas turbines can generally be divided into aero-engines and industrial gas turbines. The main components for the cycle process are the compressor stage, combustor, and turbine. In aero-engines the working fluid expands to some extent in the turbine and largely in an additional jet nozzle. The dominant factor for the efficiency of the Brayton cycle of gas turbines is the gas temperature at the turbine inlet. Figure 15 demonstrates that the efficiency of an industrial gas turbine increases with the turbine inlet temperature [22 / 23 / 24 / 25]. This means that a further improvement in the gas turbine efficiency is mainly attainable by increasing the temperature of the combustion gas at the turbine inlet. As a consequence, materials used in the turbine are exposed to higher temperatures. Typically, a gas temperature of about 1400°C leads to a temperature of the first-stage rotating turbine blades of about 800°C, down to about 650°C for the last stage (industrial gas turbine FMW 701F, [22]).

Critical engine components with regard to the demand for higher turbine inlet temperatures are in general the nozzle guide vanes and the rotating turbine blades mainly in the first turbine stage (fig. 16). In the following sections, only the main demands for these critical engine components are briefly sketched.

Nozzle guide vanes direct the hot combustion gases into the rotating stage of the turbine. Adequate service life requires active cooling and thus a complex design only achievable by casting technology. Due to mechanical loads caused by thermal gradients and aerodynamical forces, thermal fatigue resistance and creep strength are defined as the main requirements. Oxidation and corrosion resistance are realized by intrinsic material resistance and protective coatings. Thus, for new materials withstanding higher temperatures, thermal fatigue resistance and creep strength have to be improved. Standard alloys used in the past decades are cast CoCrNi base alloys, and NiCrCo base alloys due to their very good mechanical properties and their good to excellent oxidation and corrosion resistance.

Rotating turbine blades extract energy from the combustion gases, transforming it into mechanical energy to drive the compressor (aero-engine) or the generator (industrial engine). Additionally to thermal fatigue and creep effects, high cycle fatigue is critical due to the vibration phenomena and centrifugal loads. Since wrought nickel base alloys are mainly used in industrial turbines $\gamma'(Ni_3Al)$-hardening cast NiCrCo base alloys are widely used in aero-engines. New casting technologies such as directional solidification and singl-crystal casting led to an overall improvement in mechanical properties. With these techniques, grain boundary stabilizing elements such as C, B and Zr could be removed. Thus, the temperature of incipient melting and consequently the operating temperature of the alloys were increased.

However, high operating temperatures of about 80% to 85% of the solidus temperature lead to fast changes in microstructure and thus to the decrease in mechanical properties. Moreover surface degradation occurs due to corrosion and oxidation. Since Cr has to be reduced in order to allow higher amounts of γ'-hardening elements like Al, Ti and Nb, a further increase of mechanical properties in general counteracts the oxidation and high-temperature corrosion behaviour.

Thus, for higher operating temperatures, new metal composites are investigated. They are mainly based on oxidation and corrosion-resistant alloys (Ni-base, Fe-base and intermetallics) provided with finely dispersed, thermal stable second phases like oxides or carbides, which induce the strengthening effect. The best known and most investigated alloys of this category are the so-called oxide-dispersion-strengthened alloys (ODS). They promise improved creep resistance and higher structural stability at elevated temperatures [25].

As the specific weight of nickel and cobalt base alloys is high, new intermetallic high-temperature, light-weight alloys with appropriate mechanical properties and intrinsic good oxidation behaviour are under investigation. Titanium alloys were developed showing good microstructural stability up to 650°C (IMI834). But application at this temperature level was rejected due to the detrimental oxidation and corrosion behaviour. Promising candidates are alumindes of titanium (TiAl, Ti_3Al, and alloys) and nickel (NiAl, Ni_3Al, and alloys) due to their temperature potential and up to 50% less weight compared to Ni-base alloys.

Superior resistance to high-temperature corrosion and thermal fatigue and low specific weight makes silicides of molybdenum and titanium ($MoSi_2$, $TiSi_2$, Ti_5Si_3) into applicable high-temperature alloys. Fig. 17 and table 4 [24] summarize the possible applications in gas turbines and the admissible operating temperatures.

However, the development of applicable ODS and intermetallic alloys takes place in a situation of conflict between materials properties, processing capability, and the complexity of the component, such as an actively cooled turbine blade. New metal alloys such as ODS alloys pose some difficulties in producing turbine blades with complex cooling systems. Therefore some alternative research aims at increasing of the high-temperature mechanical properties by improving the purity of cast alloys for directional or single crystalline solidification. The main topic of this work is to avoid impurities caused by chemical reactions of the alloying elements with the crucible wall. Typical new melting processes are current-induction skull crucible casting and electron beam casting.

5 Materials and Processes

5.1 Ferrous Alloys

Ongoing developments in non-ferrous light-weight and high-temperature materials force the steel industry to flexibly adapt of their product qualities to customer´s demands. Up to now the standard blast furnace processes for making iron limited the flexibility to meet market variations due to the demand for maximum productivity in order to be competitive. The development of new production processes for ferrous semis, beginning with the ironmaking process and extending to the fabrication of the semis, allows new flexibility in producing custom-made and application-tailored components [26]. Thus, the base is provided for new ferrous alloys or semis. Processes under development such as the Smelting Reduction Process (SRP), the Cyclone Converter Furnace (CCF) and the Jupiter Process permit dispensing with coke production and iron ore sintering, and facilitate simplification of the process, therfore helping to avoid or reduce polluting emittant output. New computer technologies have permitted of recent developments in the continuous casting of ferrous alloys [26]. Casting strips with thicknesses down to 1 to 3 mm should be achieved. This technique allows remarkable savings in raw materials and energy and thus lower emission of harmful reagents. Additionally, a new potential method for the development of new steels is available, which could not be produced by the conventional rolling route [27].

Because of the high Young's modulus of about 210,000 N/mm^2 in addition to high yield strength, steels are excellent candidates for light-weight structures. Improved strength, cold drawability and high energy absorbtion in crash situations for automotive bodywork sheets, which are the basis for steel-based, light-weight structures, are achieved by manipulating of the microstructure with the aid of advanced materials treatments. Additionally, new alloys are under development in order to match the required demands, especially those of the automotive industry. So-called tailored blanks provide a new way of using the properties of different steel types. This combination of laser-welded blanks offers simpler production of components and necessitates simultaneous engineering between steel makers and the manufacturing industry. Nevertheless, a weight-saving potential of about 25% and more compared to today's weight of a car could be attained by substituting 50% standard steels by new high-strength steels and tailored designs [28]. Estimations of the fuel-saving effect show that reducing fuel consumption by about 0.3 l per 100 km and 100 kg are possible. A consequent transfer of the light-weight potential of high-strength steels could thus lead to a fuel saving of about $346 \cdot 10^6$ liters per year in western Europe [29].

Developing of high-strength steels with good cold drawability began in the seventies. After an initial delay due to the lack of experience in drawing processes with these new steels, they began to be applied in the automotive industry [30]. The main high-strength steels developed over the last 25 years are:

- micro-alloyed steel
- phosphorus-alloyed steel
- pot-galavanized high-strength sheets
- bake-hardening steel

Phosphorus and micro-alloyed steels are mainly applied to crash structures due to their high strength but difficult drawability. Bake-hardening steels are used for auto body sheets. The weight saving potential for these groups of steel is documented in fig. 18 [29].

Figure 19 shows the increasing demand for high-strength steel strips on the part of the automotive industry in the past ten years [30].

5.1.1 High-strength steels

In the automotive industry, high-strength steels have been used for years with a share of about 20% of the structural steels [29]. The demand for steels with higher strength led to the development of micro-alloyed (MA) steels with a yield strength of 260 - 420 N/mm^2 and phosphorus-alloyed (PA) steels with a yield strength of 220 - 300 N/mm^2 [29]. The strengthening mechanisms of MA steels are mainly fine-grain hardening and hardening through precipitation of TiN, NbC, respectively (Nb,Ti)(C,N) [31]. Strengthening PA alloys is based on solid-solution hardening. An additional rise in strength is attained through thermomechanical treatment (TMT) of V, Ti and/or Nb-alloyed alloys. The minimum yield strength extends from 340 up to 690 N/mm^2 depending on the alloy composition and the TMT. The properties and chemical composition of a typical high-strength, hot-rolled steel, micro-alloyed with Ti and V, are summarized in table 5. The effect of Ti and V comprises the adjustment of a fine-grain structure and precipitation hardening [31].

The drawback of the increased strength is the reduced cold formability. Thus, MA and PA steels are mainly used in structural, crash-critical parts. Investigations on the energy dissipation of high-strength steels show that the above-mentioned high-strength steels commonly exhibit an improved energy consumption at high strain rates. Figure 20 shows the energy consumption per volume of typical high-strength steels (hot-rolled QStE500TM, bake-hardening ZStE180BH, interstice-free, pot-galvanized alloy IF (HS)) compared to the classical deep-drawing steel FeP04 and the aluminium alloy Al5182 (Al4,5Mg0,4Mn). In all cases the high-strength steels show equal or better energy consumption compared to the standard alloy FeP04 [31]. The low values of the aluminium alloy, investigated for automotive structural applications, reveals the problematic crash behaviour of Al-based structures.

5.1.2 Bake-hardening steels

The main demand for auto body coverings is the buckling resistance, which depends mainly on stiffness and the yield strength of the steel. Additionally to the metallurgically increased yield strength and the rise in strength by cold working, bake-hardening steels harden during baking-enamelling. The metallurgy of these steels is conditioned such, that hardening occurs at temperatures above 120°C, due to controlled carbon aging. This offers good cold drawability in the unaged condition and an increase in strength of the final structural component, such as doors, fenders, and hoods. Yield strengths of bake-hardening (BH) steels commonly extend from 190 N/mm^2 up to 330 N/mm^2, tensile strength from 300 N/mm^2 to 440 N/mm^2. Strength is adjusted by alloying with phosphorus [31]. In order to attain minimum C content, BH steels are decarburized by vacuum annealing. The chemical composition of a typical representative of the BH steels (ZStE 180 BH) is given in table 6.

The drawability of typical bake-hardening steels is comparable to the deep-drawing steel St14, as is shown in fig. 21 [29]. Compared to phosphorus-alloyd or micro-alloy steels, BH steels offer higher elongation and therefore better drawability. The extent of the strengthening effect depends on the process parameters strain, temperature and bake hardening time [28]. Figure 22 documents an increase of the BH effect with both increasing temperature and time for the non-deformed state and the 2%-deformed state. An improved crash behaviour of BH steel ZStE 180 BH compared to standard cold-draw sheets results of high-strain-rate tensile tests with strain rates up to 225 s^{-1}, which corresponds to a crash velocity of 50 kmph, extends increasing energy absorption with increasing strain rate [31].

Bake-hardening steels have now reached a state where they can increasingly be used in the mass production of auto bodywork structures. They are a powerful alternative material to Al alloys with respect to the reduction of weight and thus fuel consumption of automotives as well as of production energy.

5.1.3 Tailored Blanks

Tailored blanks were introduced onto the automotive market by Thyssen Inc. Germany in the late eighties. A tailored blank is the combination of steel sheets of different quality, surface coating and thickness by laser beam welding (fig. 23). This procedure offers the possibility of combinating the different sheet properties section-wise and thus the local adaption of stiffness and strength to the required structural demands. This provides an excellent chance to reduce the weight of structural components. Yielding, easily deformable steels types can be used in crush sections, while sheet sections with higher strength and thickness are used in load-bearing sections of the structure. Fig. 24 shows the examples of tailored blanks for auto components. The sheet thicknesses are adapted to the necessary local stiffness of the respective component [32]. Fabrication of a car door, for example, by using tailored blanks leads to a weight reduction of about 0,8 kg per door [32]. A tailor-made wheel housing shows a higher life time additionally to the decrease in weight.

A supplementary benefit of the use of tailored blanks in addition to the great weight reduction potential is the reduction of finishing steps, the decrease in parts and in transportation.

Tailored blanks are currently approaching use in mass production.

5.2 Nickel Base Alloys

As mentioned earlier, Ni-base alloys are the current standard candidates for high-temperature applications such as turbine blades and turbine vanes. Their potential is the ability to harden by precipitating the $\gamma'(Ni_3Al)$-phase in addition with good oxidation resistance. However, coatings are necessary when using these alloys at temperatures above 1000°C in oxidizing atmosphere. As will be described in the subsequent chapters, oxide-dispersion-strengthened (ODS) Ni-based variants offer higher strength and fatigue resistance. The drawback of ODS-Ni alloys is the limitation in design due to the powder production route. For gas turbine blades it is necessary to design complex cooling channels [22]. Experience in gas turbine development shows that the advantages in strength and fatigue of ODS alloys are offset by the absence of efficient cooling structures due to the reduced processing capability. Based on this fact, new casting processes and Ni-base alloys are currently under development for turbine blades or vanes in order to meet the requirements for improved thermal fatigue and creep strength at high temperatures.

Developments in the casting process focus on the purity of the alloys used. The main point is to avoid impurities and the impoverishing of reactive elements such as Cr, Nb, Ti, etc. caused by the interaction between the ceramic crucible and the molten alloy. This problem is aggravated if new alloys with highly reactive elements such as Y, Hf, etc. are used [23]. Thus new melting technologies are under investigation with the aim of trying to avoid direct contact of the melt with the crucible wall. In the Current Induction Skull Crucible (CISC) and the electron casting process, which utilize a water-cooled copper crucible, a thin skin of the molten alloy solidifies on the crucible surface separating the melt from the crucible surface (fig. 25). Thus a high degree of purity can be achieved.

Additionally to the improved melting process, higher thermal gradients during directional solidification (DS) and single-crystal solidification (SCS) are applied. During DS and SCS, the melt-containing mould is moved from a heating zone into a cooling chamber providing a nearly axial temperature gradient and thus axial solidification. With the DS process, grain boundaries are also directed in axial direction. Grain boundaries running into the casting surface are therefore minimized, avoiding crack initiation sites. A next step is the formation of a single crystal using special casting starters ("pig tail"). A higher thermal gradient by using liquid metal cooling improves the microstructure (smaller dendrite spacing) and minimizes element segregation and the formation of porosity (fig. 26) [23]. For SCS the probability of more than one grain forming is reduced.

The development of new Ni-base alloys tends to reduce chromium content in order to attain the maximum solubility of $\gamma'(Ni_3Al)$-forming elements. An increase in γ'-precipitation in addition to directional solidification allows improving both thermal fatigue and creep resistance. Alloys of the third generation owe their improved creep behaviour to the addition of refractory elements like rhenium and tungsten. However, the severe segregation behaviour counteracts this effect. Thus, a directional solidification process with a high thermal gradient is necessary to exploit maximum creep resistance at high temperatures. Fig. 27 shows the possible increase in temperature capability with decreasing Cr content. The values are related to conventional cast alloy 738 (CC). A rise in operating temperature of about 110°C seems to be possible by using Cr-poor alloys in addition to the SC process [33]. However, the poor chromium content requires coatings that protect from hot corrosion attack.

5.3 Intermetallic Alloys

5.3.1 Aluminides

Ordered alloys of intermetallic constitution based on aluminium are called aluminides. The most representative alloy systems are those of titanium aluminides (Ti_xAl) and nickel aluminides (Ni_xAl) with their low-alloyed variants. They are mainly produced by conventional casting routes or powder processes (PM/HIP) and subsequent extruding. In general, high specific stiffness and ultimate tensile strength are the advantages, while brittleness at room temperature and poor creep resistance (except TiAl) of the monolithic alloys are the negative aspects of these alloys. The main disadvantage of these alloys is their lack of ductility at low and medium temperatures caused by their ordered lattice structure and the lack of active slip systems [34].

TITANIUM ALUMINIDES are the light-weight aluminides and can principally be divided into two main alloy types, TiAl and Ti_3Al.

TiAl (γ)-based alloys

TiAl consists of a major matrix of TiAl with Ti_3Al second phases. The specific weight is about 3.9 g/cm^3. The alloy systems investigated up to now are Ti + 46-52 at% Al + 1-10at% of the elements V, Cr, Mn, W, Mo, Nb,or Ta. Fig. 28 documents the lower ductility by comparing the fracture toughness of TiAl and Ti_3Al-based alloys with the Ni-base alloy In738LC and the near-α titanium alloy IMI834 [24]. Alloying with elements such as Cr, Nb, Mn and Si (e.g. Ti48Al2Cr2Nb) enhances ductility and high-temperature strength by forming a two-phase microstructure (γ (TiAl) and α_2 (Ti_3Al)). Furthermore, a complex thermo-mechanical treatment (TMT) increases the yield strength and ductility of Ti-aluminides by resulting in fine equiaxed grain and a flaw-free structure [20]. Appropriate processes to achieve fine grain are isothermal forging, extrusion or powder processing [22]. The resulting excellent specific yield strength (strength/weight) compared to Ni-base alloys and near-α titanium alloys up to 700°C is shown in fig. 29 [19]. However, specific yield strength is lower than that of the Ti_3Al-based alloy. Fatigue strength of defect-free material is very high at 80% to 90% of the yield strength. Micro-pores and notches significantly reduce life time. Applying of TiAl alloys is possible up to 750°C and thus offers a by about 100°C temperature potential higher than Ti_3Al [24].At higher temperatures, resistance to creep and oxidation is insufficient for application. Oxidation behaviour is dominated by the formation of the TiO_2/Al_2O_3 layer. The lack of Al leads to the formation of Ti_3Al, which causes embrittlement by dissolving up to 20% of oxygen.

Ti_3Al (α_2)-based alloys

The most preferred alloys are Ti_3Al alloyed with Nb, V and/or Mo for enhanced ductility. The best known and most promising is alloy Super-alpha-2 alloy Ti62Al26Nb10Mo1. Unfortunately, this alloy lacks acceptable formablity and is susceptible to hydrogen embrittlement [35]. Two phase α_2-γ alloys, stabilized by additions of Cr, V, Mo and/or Nb (e.g. Ti59Al40V), show that the most promising mechanical properties, yield strength and room temperature fracture toughness are superior to those of TiAl (fig. 29). Processes to enhance room temperature fracture toughness by grain refining are similar to those of TiAl alloys. Application of Ti_3Al alloys is limited to temperatures equal to or below 650°C, due to insufficient oxidation and strength [24]. However, further research activities show that alloying with Si up to 8,5% leads to the formation of an eutectic alloy system T_3Al-Ti_5Si_3 with improved mechanical properties and oxidation behaviour [36]. A comparison of the oxidation behaviour of Ti_3Al alloys with TiAl and other Ti alloys is given in fig. 30 [37].

Due to the above-mentioned inherent material problems, Ti_xAl-based alloys are still under development and not yet applied commercially site. A further problem is the very limited reproducibility of properties of materials from different suppliers and different batches [38]. Current activities on alloy development focus on the further improvement of room-temperature fracture toughness, formability and high-temperature creep strength. Recently, orthorombic titanium aluminides based on $Ti_2(AlNb)$ were investigated and exhibited excellent ambient-temperature formability and high-temperature mechanical properties. A cold reduction of 40% to 80% and a specific strength 50% to 75% greater than Inconel Alloy 718 at

700°C is reported [35]. TiAl alloyed with 0.3% Sb and 0.5% Hf exhibits superior high-temperature strength of about 280 N/mm^2, with specific gravity only rising from 3.8 to 3.9 g/cm^3. The lack of sufficient creep strength of both types of alloys TiAl and Ti_3Al at elevated temperatures above 600°C makes resarchers apply the method of oxide dispersion strengthening to aluminides.

NICKEL ALUMINIDES can mainly be divided into the two alloy groups NiAl and Ni_3Al. In contrast to the Ti aluminides, Ni aluminides, beside low room temperature ductility feature insufficient strength and creep resistance at high temperatures [39]. However, with densities of about 5.9 g/cm^3 (Ni_3Al) to 7.7 g/cm^3 (NiAl), they exhibit a weight reduction potential of up to 25% compared to Ni-base superalloys.

Ni_3Al

Despite the sufficient room temperature ductility attained of about 10-15% for boron-doped Ni_3Al, this type of alloy was mainly rejected in the investigations. This is due to low creep resistance at elevated temperatures and the embrittlement at 600°C to 700°C [24]. Thus, investigations are focussing on the Ni aluminide type NiAl.

NiAl

NiAl exhibits an excellent oxidation and corrosion behaviour up to 1300°C. Additional advantags compared to Ni-base superalloys are a 4-times higher thermal conductivity, a lower coefficient of thermal expansion (CTE), and the reduced specific weight. A further benefit is the better resistance to thermomechanical fatigue. However, high-temperature strength of about 40 N/mm^2 at 1000°C , creep strength at elevated temperatures and room temperature fracture toughness are poor [40]. To improve this situation, NiAl is alloyed with elements and with metallic, respectively intermetallic phases. However, enhancing strength by solid solution strengthening with alloying elements like Cr and Nb will only be mediocre because of the low solubility of Cr and Nb. Alloying with Cr, Mo, W, Ta and Nb enhances strength and fracture toughness through the formation of second phases [41, 42]. A typical alloy is NiAl-Cr. The formation of eutectic phases of NiAl-Cr and processing with directional solidification or powder metallurgy routes improves high-temperature strength and ductility. Figure 31 documents the increase of 0.2% proof stress with the rise in Cr content and its temperature behaviour [36]. Unfortunately, the increasing Cr counteracts oxidation resistance [36]. Processing the alloy greatly influences strength and fracture toughness due to microstructural effects such as grain size, second phase distribution, etc.. Fig. 32 reports on the difference in elongation and fracture toughness depending on processing (HIP resp. HIP and extrusion).

The above-mentioned facts give distinct picture of the situation, namely that the main problems of Ni aluminides that have to be solved are the low room-temperature ductility and the high-temperature creep resistance. An approach for solving the brittleness at ambient temperatures is the concept of ductile phase toughening. By dispersing ductile particles of, for instance, Cr and Nb in the brittle material, the crack resistance should be enhanced, leading to a quasi-ductile material behaviour [43]. Investigations on NiAl+5%Cr and NiAl+5% Nb particles show that there is an toughening effect, but it is only metastable. After exposure to temperatures higher than 1000°C Nb and Cr particles become as brittle as the NiAl matrix due to solid-solution reactions [43]. This means a limit to operating temperature well below 1000°C. However, research in the fields of ductile phase toughening is continuing. A promising solution for the creep problem is to strengthen the matrix by adding oxide dispersoids (see chapter on ODS alloys).

5.3.2 Silicides

Low densitiy and the oxidation resistance of silicides due to the formation of a protective SiO_2 scale on the surface makes silicide a potential candidate for light-weight components operating at moderate temperature in an oxidizing environment. Possible applications are, as mentioned above, oscillating masses like pistons. However, silicides lack room-temperature ductility, like all intermetallic phases. Therefore most research activities are driven by the demand for improved room-temperature ductility and easy processing. In the following paragraphs, some engine-component-related alloys and their advantages and disadvantages are described.

Al-Mg_2Si and Mg-Mg_2Si

The search for new piston alloys with high thermal stability, good high-temperature strength and low specific weight points toward the intermetallic phase Mg_2Si. Due to the inherent room-temperature ductility Mg_2Si, utilizing the monolithic intermetallic is not possible. Thus, with respect to ceramic-fibre or particle-reinforced materials (MMC's), a composite of Mg_2Si with either an Al matrix or an Mg matrix was produced and investiagted [18, 44].

Both alloys are produced by squeeze casting, grain refined by the addition of 1wt% phosphorus. A maximum of about 30vol% Mg_2Si can be achieved by the casting process. Both alloys offer the advantages of lower thermal conductivity, a moderate CTE and a lower specific weight compared to the die-cast standard piston alloy AlSi12CuMgNi. Ductility is only sufficient with high amounts of Mg, respectively Al. Following the mixture rule, Al-Mg_2Si exhibits a higher Young's modulus than the AlSi-based alloy. The Young's modulus of Mg-Mg_2Si is lower compared to the standard AlSi piston alloy, but consequently higher than that of alloy MgY5.2RE3Zr0.7 (WE54). Fig. 33 shows a lower drop in Young's modulus with increasing temperature compared to the standard piston alloy [44]. The behaviour of the yield strength of Mg-Mg_2Si is documented in fig. 33. In the temperature range of about RT to 270°C, the Mg-Mg_2Si alloy shows a significantly lower yield strength compared to the standard piston alloy and alloy WE54 [44]. At $T > 270$°C the Mg composite is superior. A comparable behaviour of tensile strength and fatigue strength is reported for the Al-Mg_2Si alloy [18]. The CTE is reduced with increasing volume fraction of Mg-Mg_2Si, as is shown in fig. 34 for Al-Mg_2Si. Additionally the CTE of Al-Mg_2Si is lower than that of the AlSi alloy. This offers the possibility of reduced piston play.

The above-described properties of the Al-resp. Mg-Mg_2Si alloys show that the specific strength is superior to that of the standard piston alloy. This means a weight reduction of the piston of about 10% with Al-30%Mg_2Si and 30% with Mg-20%Mg_2Si. Additional benefits are the lower CTE and the good processing capeabilities. However, these types of alloys have been under investigation up to now and have not yet been incorporated in prototypes and mass production.

Molybdenum Disilicide $MoSi_2$

$MoSi_2$ is commonly known as an intermetallic alloy for use as an oxidation protection coating for high-temperature applications and is produced by vacuum plasma spraying (VPS). However, there are multiple possibilities for using of this type of alloy for high-temperature components in turbines or combustion chambers [45]. The most promising processes are hot isostatic pressing (HIP) with optimized pressure and temperature control, metal injection moulding (MIM) with type-true sinter additives and SHS (self-propagating high-temperature synthesis) [46]. All these process routes aim to produce near-net-shape parts.

$MoSi_2$ offers excellent corrosion and oxidation behaviour in oxidizing atmosphere at temperatures up to 1600°C, due to the formation of a dense SiO_2 surface layer. Under continuous thermomechanical load, a maximum operating temperature of about 1200°C is achievable [45]. Due to the covalent-metallic bond, $MoSi_2$ exhibits high thermal conductivity (24.1 W/mK at 1200°C) and sufficient room-temperature strength of about 320 MPa. However, as with every intermetallic ordered phase, the covalent atomic bond component causes low ductility below the ductile-brittle transition temperature (DBTT). The fracture toughness at room temperature is about 4.7 MPa$\sqrt{m}$. Due to the influence of the microstructure on the mechanical properties of $MiSi_2$ alloys, oxidation stability is based to a very great extend on microstructure and porosity. Spalling of the SiO_2 surface layer and severe surface degradation are observed in a temperature range of about 600°C-700°C. Hence, careful processing is necessary to take full advantage of the alloy's oxidation resistance.

Since investigation of bulk $MoSi_2$ materials is just starting, only few data are available. But investiagtions on second-phase strengthened alloys such as $MoSi_2$-WSi_2, respectively $MoSi_2$-SiC, are under way [45].

5.4 Dispersion Strengthened Alloys

DS alloys consist of a matrix of an alloy or a pure metal with finely dispersed, insoluble and thermal stable second-phase particles (mainly carbides or oxides) some ten nanometers in size. The reason for developing these alloys is to improve strength and creep resistance at high temperatures by up to 90% of the alloy's melting point, compared to 40% for strain-hardened alloys and 60% for precipitation-hardened alloys. Recent inverstigations show that the dominant strengthening mechanism is the attraction of the dislocations to the particles and a resultant partial relaxation of the stress field produced by the dislocation [25]. A maximum strengthening effect is attained, reducing the diffusion-controlled creep by producing microstructural texture.

DS alloys are produced by mechanical alloying. A certain ratio of powders of the reinforcing oxide and the matrix alloy are mixed and subjected to long-term milling in a ball mill or an attritor mill. During this process the metallic particles are strongly deformed, cold-bonded, including the second-phase particles, and crushed. The constituents of the original powder mixture are thereby dispersed submicroscopically. Temperature and gaseous medium (Ar, N_2, vacuum, etc.) in the mill depend on the materials processed. The resulting composites are commonly processed by cold isostatic pressing (CIP), hot isostatic pressing (HIP) and extruding. In some cases thermomechanical treatment adjusts the required microstructure.

Different DS alloys are investigated extending from pure aluminium, respectively aluminium alloys, to γ'-hardenable Ni-base alloys, Fe-base alloys and finally to the above mentioned Ni-aluminides.

Oxide Dispersion Strengthened-Aluminium Alloys

Oxide-dispersion-strengthened (ODS) aluminium is produced by milling pure Al powder with Al_2O_3 particles under cryogenic conditions with liquid nitrogen. The volume ratio of the oxides is 3 vol%. The resultant ODS powder is subsequently treated by PM/HIP processes and/or extruding.

This ODS aluminium shows some very good high-temperature properties. The result of tensile tests is a higher UTS of the ODS-Al compared to that of alloy Al7475-T61 at a test temperature above about 200°C (Fig. 35) [47]. Creep tests show that when subjected to a load of 160 MPa a strain threshold of about 0.3% is reached at a proof temperature of 275°C (Fig. 36). This behaviour is caused by grain pinning by the oxide particles and nanocrystalline aluminium oxynitrides formed in situ [47]. The elastic modulus changes only moderately with the volume content of the second phase fraction.

Oxide and Carbide Dispersion Strengthened Al Alloys

Typical alloys of this type are summarized in table 7.

Dispersion strengthening is based on the formation of both Al_4C_3 and Al_2O_3 during the mechanical alloying process [48, 49]. Optimum mechanical properties are attained without subsequent heat treatment after the extrusion process. Room-temperature tensile strength reaches about 400 MPa, depending on the matrix alloy and the volume fraction of dispersoids. However, increasing strength is accompanied by a drop in elongation and thus ductility (fig. 37) [50]. Fig. 38 shows the superior strength of DS Al alloys at temperatures above 150°C compared to a conventional piston Al alloy AlSi12CuMgNi. A specific phenomenon is the drop in elongation with increasing temperature. A severe decrease in tensile strength with increasing temperature is reported to appear above 400°C [50]. Fatigue strength of about 80 to 95 N/mm^2 at 350°C is reported, which is superior to that of standard Al alloys. Reduced crack initiation and growth during thermal cycling leads to superior thermal fatigue resistance compared to standard piston Al-alloys [50]. Up to now no mass-production application of this type of alloy is known, but components like pistons, con rods and cylinder head inserts have been tested.

However, contary to the Ni-base ODS alloys exhibiting operating temperatures of about 90% of their melting point T_S, ODS-Al alloys just reach temperatures of about 50% T_S [25]. The interest in new "high-temperature" Al alloys for structural applications calls for further inverstigations on ODS-Al.

ODS Nickel Base Alloys

Based on the first classical Ni alloy TD nickel (pure nickel with 2 vol% thoriumoxide), new alloys like MA 754 and MA 6000 were developed. The alloys are produced by mechanically milling the Ni base alloy with Y_2O_3 particles and subsequent thermomechanial treatment like HIP or extruding in order to attain an optimum microstructure. Contrary to the strengthening γ' particles, the oxides do not dissolve in the alloy matrix at elevated operating temperatures. Additionally, grain growth is hindered by the inherent oxides due to grain boundary pinning. However, in alloy MA 6000 both strengthening mechanisms, oxides and γ' hardening, are used in order to attain maximum creep strength at high temperatures. Fig. 39 shows the 1000h creep strength for alloy MA 6000 to be superior to that of the classical Ni-base alloys [21]. Because of the thermal stability of the inert oxide particles, the alloy is applicable at a temperature up to 1100°C -1150°C, which is near the melting point of the alloy. But, as mentioned above, oxidation protection coatings are necessary for such high operating temperatures.

ODS NiAl Alloys

As attempts to strengthen NiAl-based matrices by solid solution hardening or precipitation hardening mechanisms failed for low strain rates and high temperatures [51, 52], new approaches are being pursued concerning oxide dispersion strengthening. ODS-NiAl and NiFeAl alloys are reported to be produced by mechanical alloying with 1% to 2% Y_2O_3 dispersoids. The experiments on mechanical alloying and hot isostatic pressing (HIP) show the possibility of producing materials with a fine grain in the micrometer range [53]. The influence of the oxide disperoids on creep behaviour is currently under investigation.

ODS Iron Base Alloys

ODS alloys based on ferritic Cr steel have been developed for high-temperature applications. The reason for such development was the above-mentioned mediocre oxidation resistance of high-strength Ni-base casting alloys and ODS Ni-base alloys. Conventional ferritic steels with a high content of chromium posses excellent oxidation behaviour. Thus, ferritic ODS Fe-base alloys like MA 956 and PM 2000 were developed consisting of Fe20Cr4,5Al0,6Ti (MA 956), respectively Fe20Cr6Al0,6Ti (PM 2000) and 0,5% finely dispersed Y_2O_3 particles [54]. The alloys are generally produced by mechanical alloying, compaction, deformation and final recrystallization. These alloys exhibit excellent oxidation and corrosion resistance up to temperatures of about 1250°C by forming of adherent, stable Al_2O_3 oxide films [55]. However, the creep strength of MA 956 amounts to about 60% of the values attained with Ni-ODS alloy MA 754 at temperatures between 1000°C and 1100°C, but extends up to 1350°C [21]. The maximum operating time in combustion gas atmosphere for MA754 is about 7500 hours at 1250°C [55]. PM 2000 shows better oxidation resistance, due to the higher Al content and very good creep behaviour at temperatures up to 1250°C. For both types of Fe-ODS alloys, production and the resulting microstructure significantly influences the final high-temperature properties. Fig. 40 compares the creep strength of both alloys with Ni- and Co-base alloys and with the Ni-ODS alloy MA 754. The Ni-ODS alloy exhibits higher creep resistance, but ferritic Fe-ODS is applicable up to 1250°C. Note that Ni-ODS alloys must be coated for operating temperatures from 1000°C to 1100°C.

Alloy PM 2000 is currently about to be applied to some thermally loaded components of automotive engines in mass production.

Nevertheless, world-wide investigations on ferrous ODS alloys are continued. Japanese researchers have report on the production of a particle-dispersed steel with the highest Young´s modulus ever reached for steel of about 265 to 285 GPa [56]. This Fe,13-16Cr,1-3Al, 0.5(Y_2O_3+Yb_2O_3)-based steel is produced by three-stage processing consisting of mechanical alloying with the above-mentioned oxides, hot extrusion and subsequent heat treatment at 1200°C to 1400°C. Yield strength is about 600 MPa to 900 Mpa and UTS about 700 MPa to 900 MPa. The alloy can be fabricated as bars, pipes or sheets.

5.5. Light-weight Alloys

5.5.1. Aluminium Alloys

Developments in aluminium technology are very rapid. Today´s major research fields are the optimizing and modification of known alloys and the development of new process technologies to increase productivity <u>and</u> properties in one step without higher costs. The casting technology is a good example of the last-mentioned development line. New casting technologies like thixoforming or thixomolding are approaching large-scale production. The die-casting process today allows nearly pore-free manufacturing of castings in extremely short time cycles.

The aluminium wrought alloys are of increasing interest even for the automotive industry. They offer high strength and toughness, often in combination with good weldability. On the other hand, cast alloys are much cheaper because they do not have to be of such high purity and processing is easier. So the wrought alloys are only used when they are really needed.

Aluminium-Lithium Alloys

Aluminium-Lithium alloys offer advantages such us low density and high modulus. Lithium is the lowest-density metallic element (ρ=0.534 g/cm^3). Therefore alloying with lithium will lead to a reduced density of the alloy gained in this way. For example, a lithium content of 2.5% leads to a weight reduction of about 10% [57]. In the past 15 years much research work has been focused on these alloys, but their impact on the aerospace market has fallen short of initial expectations. Part of the reason is the lower fracture toughness and stress-corrosion resistance of the actual AlLi alloys compared with conventional aerospace-quality aluminium alloys [58].

New technologies (vacuum refining) are under development to obtain high-purity alloys with high lithium contents of up to 3.3%. It seems that aluminium-lithium alloys are very sensitive to impurities, especially hydrogen and alkali metals. Fig. 41 [58] shows the increase in the purity of the alloys and the improvement in fracture toughness. As mentioned earlier, the fracture toughness is an important factor for aircraft engineering.

High-Strength Aluminium Alloys

The high-strength aluminium alloys are undergoing continuous development. Especially the alloys of the 7xxx series are of great interest because of their excellent fatigue behaviour and their high-strength. Table 8 gives a classification of the currently used high-strength aluminium alloys in aerospace applictions.

In the development of high-strength aluminium alloys, the powder metallurgical route offers one of the most interesting ways to obtain even higher strength in combination with increased fracture toughness than today. Rapid solidification technologies lead to a combination of different hardening mechanisms because of the supersaturation of the solidified material. The volume content of the particles containing Zn-Mg-Cu in AlZnCuMg alloys of the 7xxx group could be increased. This leads to an improved precipitation hardening effect. The addition of elements like Zr, Mn, Cr, Fe or Ti leads to the formation of intermetallic phases and therefore to additional strengthening. With the next step in powder metallurgical processes, mechanical alloying, it is possible to alloy elements which are not soluble in any thermodynamic state (e.g. alloying of graphite and aluminium without getting Al_4C_3) [57]. The adavantages of PM-aluminium alloys are obvious when compared to conventional ingot alloys (table 9). The alloy 7093 is a PM alloy based on the aluminium-iron-cerium system [59].

The powder metallurgy processes have the disadvantage of high cost. On the other hand, some light-weight or high-temperature problem areas cannot be solved without the use of such materials. In future, the need for highly developed, advanced powder aluminium products may increase. Until now none of PM processes are of any use for big parts like whole engine blocks.

From the above it is possible to derive the demands that have to be fulfilled by future aluminium wrought and cast alloys as well as PM products:

- High-strength
- High fracture toughness
- High crack-corrosion resistance
- Low density
- High Young's modulus

and especially for cast alloys:

- Low price
- High ductility in the as-cast condition
- Excellent castability in sand-, permanent mould- and die-casting processes

5.5.2. Magnesium Alloys

The use of magnesium alloys is, as mentioned before, growing continously. In fig. 42 [60] the North American magnesium die cast alloy consumption is to be seen. If this course is followed in coming years, in future the importance of magnesium will increase greatly.

The magnesium alloys can be divided into three major groups:

- Standard casting alloys, based on the MgAlZn system (Azxx alloys) and its related systems MgAlMn (AMxx) and MgAlSi (ASxx).
- The higher-strength alloys, based on MgZnREZr, MgAgREZr and MgZr. These materials contain rare earth metals and partly offer unusually high damping performance
- The creep-resistant Mg cast alloys MgZnREZr, MgAgREZr and MgYREZr can reach operating temperatures up to 150 - 300 °C

The yttrium-containing alloy is the most creep-resistant light-metal alloy in the group of magnesium and aluminium alloys [61].

Fig. 43 [61] shows the mechanical properties of some selected magnesium alloys compared to selected aluminium alloys. The high-temperature tensile strength of the above-mentioned yttrium-containing alloy is obvious.

It should be mentioned that the last two alloy groups are very expensive wrought alloys. A look at the utilization trend for magnesium alloys shows that the market relates mainly to cast alloys of the first group (Mg-Al-Zn=>AZxx, Mg-Al-Mn=>AMxx, Mg-Al-

Si=>ASxx). Because of their better properties (corrosion and strength), the AM alloys will increase in importance, see fig. 44 [60].

A property catalogue for new magnesium alloys can be derived from the above:

- Excellent die-castability
- Creep-resistant up to 150 °C (minimum)
- Fracture toughness and ductility must fulfill safety requirements for automotive applications
- A recycling market for magnesium has to be established
- Corrosion resistance in the order of aluminium alloys
- High availability (because main market is the automotive industry)
- Stable and low price (whole production process for the part does not have to be more expensive than with aluminium)

Some fundamental assumptions have to be guaranteed for the production of the raw material magnesium. A lot of electric energy is needed and therefore the price of the magnesium produced and the resultant pollution of the environment are determined by the availability of cheap and clean elelctricity.

Magnesium offers many economic and ecological advantages when in the producing area:

- Electricicty generated through water, solar, or windenergy...
- Seawater...

are available [62].

5.5.3. Reinforced Light-weight Alloys

Metal matrix composites (MMC's) have tremendous potential for the future. These materials provide better mechanical properties than their matrix materials alone, and tailorable physical properties. Particulate composites can be fabricated using a variety of low-cost, net-shape processes. Continuous-fibre composites offer low density, high-strength, and stiffness at elevated temperatures [63]. The three most important light-weight alloy systems aluminium, magnesium and titanium are suitable for reinforcement. An overview over these three groups is given in table 10.

The most interesting MMC's are those that consist of fibres or particles in a common matrix material. They have significant advantages over monolithic metals and polymer matrix composites (PMC's). Compared with monolithic metals, they have a higher strength/density and stiffness/density ratio. They offer tailorable CTE, electrical and thermal conductivity and they resist wear better than the matrix material alone. The creep resistance is also increased [63].

Because of their anisotropic structure, the long-fibre reinforced metals feature an anisotropic property profile. The particulate MMC's, when not extruded, are isotropic.

The main parameters influencing a particulate-reinforced MMC's properties are given in table 11. When it is possible to control the effects of these parameters, the MMC's might really be called "Tailored Materials". The problems in long- and short-fibre-reinforced MMC's are comparable.

Production processes

The following process technologies were all developed for aluminium matrix systems. Today most of the MMC's are based on an aluminium matrix, although many of the process technologies can be transferred to magnesium, too.

The main disadvantage of MMC's is the complex solidification process in production and machining. Essential is a strong connection between particle and matrix. This interface should be in thermodynamical balance to obtain a stable microstructure at elevated temperatures.

The major production processes for particulate reinforced MMC's are [64]:

In Powder Metallurgical Processes, a pre-consolidated green body consisting of the metal matrix and the reinforcement is sintered or hot isostatically pressed (HIPed). Sometimes a mechanical alloying process is carried out before solidification.

By the use of mechanical alloying it is possible to alloy non-soluble elements due to the fact that alloying is carried out at temperatures below the solidus-temperature. The mechanical alloying process is a long term process, where usually mixing times between 2-4h are necessary. Normally the particles have dimensions of 1-3 µm. The optimum size of the matrix powder is about 2 times that of the reinforcement. Coarse matrix powders (>50µm) lead to the formation of large particle free zones in the composite [65] and therefore to inhomogenuous material properties.

The next step in the solidification process is pressing. Due to the poor thermal conductivity the powders have to be cold pressed firstly. Pressures in the order of magnitude of 500-600 MPa are used in this step. Then the powders have to be encapsulated and degased to pressures of about 10^{-5} mbar. Afterwards sintering or hot isostatic pressing is carried out at temperatures up to the solution treatment temperature of the material. In the HIP process pressures of up to 1000 bar are used. The PM products are usually reported to be fine-grained and homogeneous [65]. At the moment they deliver the best available metal matrix composite products. A description of the process technology is given in figure 45 [65].

Infiltration Processes are used to produce particulate- or fibre reinforced MMC's by infiltration of pre-forms with liquid metal. Usually, minimum reinforcement volume contents of 45% are necessary due to the mechanical stability of the preform. The infiltration can be carried out under high pressure or under gravity. The process is usually a long-term process and therefore formation of intermetallic phases or oxides is a great problem in this technology as well as chemical reactions between fibre and the melt. The infiltration time is usually about 1 second per mm^2 infiltration cross section [66]. In most of the process types a defined atmosphere (Ar, N_2) is necessary due to oxidation. One of the most important infiltration processes today is the squeeze-casting process. The high pressures in squeeze-casting (up to 1000 bar) are necessesary to obtain a pore-free material. Another approach in infiltration technologys is the use of low-pressure investment-casting to infiltrate bundles Al_2O_3-fibres.

In Spray Deposition (Osprey-Process) a liquid aluminium melt is atomized by an inert gas. The melt is over-heated to about 750 - 800°C, the reinforcement particles are fed directly into the beam of molten metal after the nozzle. The goal of the process is to produce materials with a grain-size between that of melt-metallurgical and powder metallurgical products. The molten particles are solidified on a cooled substrate, cooling rates of about 10^3 - 10^5K/s can be reached - in comparison PM offers a cooling rate of about 10^8 K/s. In the as-sprayed condition, the density of the material is about 95 - 98%, therefore the pre-solidified material has to be extruded before use because of its porosity and low ductility [see 65].

In comparison to powder metallurgical products the oxygen content of the solidified material is, in the case of aluminium, 10 - 20 times lower. Currently (1995) the sprayed bulks have a diameter of up to 300mm, a length of 1m and a weight of about 400kg and only two production plants producing aluminium MMC's are known.

The major economical problem in the Osprey process is the so-called overspray. Usually 30 - 50% of the melt are of no use for the production process because it does not hit the cooled substrate.

The in-situ process features the advantage that the reinforcement (e.g. particles) is not supplied to the melt but formed in the melt by a chemical reaction. An example is the formation of TiB_2 in a aluminium (AA 6061) melt. The in-situ process technology is very sensitive to impurities in the basic alloy and the process parameters. In future, the importance of in-situ MMC's may increase because of their specific properties. They offer

- Small particle sizes (<3µm; common particle sizes in other MMC's are >15µm)
- Thermodynamic stable interface particle/matrix and
- Low price, because most of the process is the same as in conventional wrought product fabrication.

For the scale of clarification, the smaller the particles, the better is the fatigue behaviour of the composite. "Big" brittle particles, as in the most common particulate-reinforced aluminium alloys, lead to low ductility and fracture strength. Research and development in these areas are being pursued increasingly at the moment. If these materials can keep what they promise, a big market will grow for these materials over the next few years.

THE MELT METALLURGICAL PROCESS is the cheapest solidification process for aluminium-based MMC's. The best known process is the Duralcan process: A conventional cast alloy like AA357 or AA380 (AlSi-base alloy group) is used and the particles (SiC is always used in an AlSi matrix due to thermodynamical necessities) are supplied to the melt. The particles are distributed under vaccum by mechanically stirring the melt. The stirring process is usually carried out for a time of up to 70min. The so obtained MMC's can be cast in conventional moulds and therefore they are cheap. Currently the price of 1kg is about two times that of a conventional AlSi cast alloy. Typical properties of cast MMC in comparison to the unreinforced matrix are shown in fig. 46 [67]. This type of MMC may allow large-scale production in the automotive industry.

Properties of Reinforced Aluminium Alloys

One of the most important benefits of reinforcement is, as mentioned before, the increase of Young's modulus. When using long-fibres the strength in fibre orientation direction also increases. In 50 vol.% alumina fibre (diameter 100 µm) reinforced AlZn alloy, produced by investment casting infiltration process, a Young's modulus of more than 130 GPa and a maximum bending stress up to 900 MPa was measured.

The reinforcement by the use of particles causes an isotropic change in the properties, although the strength does not increase significantly. Only sometimes the yield strength increases a little, depending on the production process. The increase of elastic modulus at constant tensile strength can be seen in fig. 47 [65]. It can be seen that the yield strength is in the case of PM material lower than in the conventional wrought alloy. Typical properties of some advanced PM-aluminium MMC's are given in table 12 [59]. The most important property of these alloys are the high elongation combined with high modulus and yield strength. This combination of properties is only available with particulate reinforced aluminium when it is produced by the use of powder metallurgy. Note that the CTE is a function of the particle volume content. Unreinforced aluminum has a CTE of $23x10^{-6}$, the reinforced alloys offer a CTE in the order of magnitude of $16\text{-}18x10^{-6}$ [59].

The improved wear resistance of particulate-reinforced AlSi alloys makes it possible to use the material in brake systems. The high thermal conductivity of aluminium (4 times that of grey cast iron) keeps the temperature in the operating range of the matrix material. This is the first large-scale application for reinforced aluminium. Fig. 48 shows the improvement in wear resistance caused by ceramic particles [68].

In comparison to other materials of light-weight engineering interest, long-fibre reinforced aluminium alloys offer excellent properties due to theire high strength and stiffness in fibre orientation direction. Fig. 49 [69] shows this type of composite in comparison to other light-weight construction materials.

Reinforced Titanium

Titanium is usually reinforced with SiC in continuous fibre form. The fibres are coated by electron-beam deposition with high-purity Ti-6Al-4V in a controlled atmosphere [70]. The cross-section of a typical $Ti6Al4V/SiC_{fibre}$ composite is to be seen in fig. 51. The core in the middle of the white SiC fibres consists of tungsten. A tungsten core is necessary in the production process of SiC monofilament fibres. After coating with Ti-alloy the fibres are consolidated applying the HIP process. As with aluminium, the reinforcement of titanium leads to higher operating temperatures and to higher strength in fibre orientation direction. Therefore the material is useful in landing gear applications or as a fan-blade structure in modern turbine engines.

It should be mentioned that currently the cost of this group of reinforced metals is extremely high (up to 1000 US$/kg). One reason for this is the high price of the fibres, developments concerning the production process of SiC-fibres are in progress. In future it may be that the major market for titanium-matrix composites will be enlarged from advanced military jet applications to civil applications and therefore to a wider market.

Reinforced Magnesium

The reinforcment of magnesium by the use of particles or fibres is one of the most interesting parts in future material development.

The disadvantages of Magnesium like

- low creep resistance
- low stiffness
- low wear resistance

can be increased significantly by reinforcement.

These material group will be an approach to lower structural weight and offer a great field of applications. Especially in the aerospace industry, where the amount of magnesium products is relatively low, these improved properties may increase the use of magnesium.

Currently the company MEL in Great Britain is developing a SiC particle reinforced magnesium alloy to reach higher operating temperatures for the use of magnesium in gear housings and engines of automotive systems. The volume content of the reinforcement is in the range of 10-20%, typical particle size is about 10 - 15μm [71].

6 Summarizing Discussion

6.1 Materials For Light Weight Structures

The research and development activities for new Al alloys and Mg alloys show, that there is a growing demand for weight reduction in both the aerospace industry and automotive industry.

Favorite Al alloys are the AlLi alloys with reduced specific weight and increased specific stiffness due to Li, or the aluminium magnesium scandium alloys which prove to combine high strength and weldability with excellent fatigue behaviour. Especially in high performance parts like automotive engines an increasing amount of high strength PM aluminium powder products may be used.

The development of creep resistance magnesium alloys with good die-castability will be on of the most important fields in the development of new Mg alloys. Although today the usage of magnesium for parts working at elevated temperatures in the range of up to 150°C, for example in gear housings, is not possible due to the poor creep-resistanceof the material, in future these application fields will be of growing interest for the automotive industry. New alloys containing rare earth metals provide well creep-resistance combined with high damping performance.

The use of reinforced light-weight alloys will increase in the same rates, that cheap process technologies (like the Duralcan-process) will be available. The tailorable properties of the material offers an on-the-problem-oriented design and therefore a high weight/stiffness or weight/strength ratio. Especially the development of long-fibre and particulate reinforced magnesium is a very important development route. The disadvantages of magnesium (low stiffness and poor creep-resistance) can be managed with this approach. The usability of magnesium will increase and therefore new application fields can be reached.

It does not have to be forgotten, that intermaterials competitions are won or lost not only on the basis of raw material price, but also on the base of total lifecycle economics of finished systems, as shown in fig. 50 [72]. Therefore, for instance, airplanes are made of aluminium rather than steel, not because aluminium is a cheaper raw material or costs less to fabricate, but rather because the lifecycle cost of aluminium aircraft is less than that of steel aircraft. For the same reason, most car bodies are currently made of steel sheet rather than aluminium. In automotive applications, lifecycle economics are very different from those in airplanes; however the same principles of material selection apply [72].

The recycling problems and the high primary energy consumption of the Al-alloy production are critical aspects delaying the introduction of Al-alloys into automotive mass production of structural components. However, research in automotive Al-structures pushes the steel makers to develop new steels and processes for steel based light weight structures. Due to high strength, excellent crash behavior, low energy demand for steel production and the nearly closed recycling loop, steels are excellent candidates for light-weight structures. New processing routes offering flexible reactions to the changing demands of steel processing industries give a new perspective for the "old" metal steel. The new processes also allow a much more easier development of new alloys and accelerate steel research. New computer aided designing, including computer simulation, allows engineers to take maximum use of the steel properties. These tendencies and the use of tailored blanks and steel types with higher strength offer a excellent base for new light weight structures in all ground transportation industry. Comparison of steel based solutions of light weight structures with the development of Al-based solutions (e.g. Audi spaceframe) show that steel is a strong competitor.

The advantage of the steels is the nearly 100% recycling in Europe and North America. This means a primary energy and raw materials saving production. Calculating the whole energy bilance of the production process, the use of secondary Al-alloys must be increased from actually 35% (Germany) to 70% in to order to compete with the steel solution in environment compatibility and cost [73, 29].

6.2 Materials For Increased Efficiency of Thermal Engines

The Ni-base alloys are commonly the work-horses of high temperature materials. However, the demand for higher temperatures above 1000°C involves problems like oxidation, transformation of the microstructure and resulting creep. One way to solve these problems is the mechanical alloying of the Ni-base matrix with oxides of yttrium. This leads to a creep resistance superior to that of the unreinforced alloy and a maximum operation temperature of about 1150°C. However, these temperatures necessitate coatings in order to avoid oxidation and hot gas corrosion. Drawback of this ODS alloys is the reduced possible complexity of the component design. For turbine blades, the excellent creep properties are counteracted by reduced cooling functionality. Thus, new casting technologies for pure γ'-hardening Ni-base alloys with higher purity are under development. They offer the full design field of cast components with improved high temperature properties. However, precipitation hardening is only a temporary strength effect due to the thermodynamical instability of the precipitations at high temperatures.

High specific weight and thus weight of Ni base alloys involves investigations on aluminides for high temperature applications. Background is the reduction of mass and thus mass forces of oscillating parts in addition to operation at high temperatures. The specific yield strength of both types of aluminides Ti_xAl_y and Ni_xAl_y are superior to that of the Ni-base alloys and the titanium alloys at temperatures from 700°C (Ti-aluminides) up to 1000°C (Ni-aluminides). However, drawbacks like inherent room temperature brittlness, the difficult formability, the very limited reproducability of mechanical properties (Ti_xAl_y) and the lack of sufficient creep resistance delay their use in high temperature applications. A lot of investigations are done to solve the problem of brittlness by the addition of alloying elements or second phase ductilization. Recent investigations on Ti_2(AlNb) show very promising results concerning formability and room temperature properties. However, in some cases alloying for improved mechanical properties counteracts the oxidation resistance. To improve the creep behavior, the process of oxide dispersion strengthening is applied to aluminides, especially to Ni-alumindes. The fine dispersed, thermodynamically stable oxides should avoid grain boundary migration. However, mechanical alloying and the subsequent powder metallurgy route is complex and expensive. Up to now, non of the described aluminides has been transfered to mass production. A lot of further investigations on metallurgy, processes and quality control have to be done in order to attain the required materials properties.

Comparable with the aluminides, intermetallics based on silicium (silicides) offer the advantage of a hughe weight saving potential ($MgSi_2$) and high operation temperatures ($MoSi_2$). Unfortunately silicides show the same poor ductility at room temperature as the aluminides due to the ordered lattice structure. $MoSi_2$ as a structural material offers operation temperatures up to 1200°C with sufficient strength and excellent oxidation resistance due to silica layer formation. However, room temperature brittlness, sever oxidation in the temperature range of 600°C (pesting) and the difficult processing of bulk materials necessites further detailed research work. Because of the poor room temperature ductility of silicides $MgSi_2$ is used as a reinforcing second phase in Al and Mg, produced by an in-situ reaction. The use of Al-$MgSi_2$ and Mg-$MgSi_2$ alloys for automotive pistons provide a weight saving potential of up to 30% compared to the standard piston alloys. This means an improved efficiency of the engine and thus reduced reagant and particle emission. Additional benefits are the higher stiffness, contributing to the weight saving, reduced CTE, higher thermal conductivity and efficient production by the casting route. Because of their properties and their cost efficient production route they have good chances to be used in serial production.

Besides oxidation behavior and thermodynamical stability of the microstructure, creep resistance is the most dominating factor for high temperature materials. Creep occures at 150°C for Al- and Mg-alloys as well as at temperatures above 1000° for Ni-base and Fe-base alloys. Oxide dispersion strengthening by inherent, thermodynamically stable oxides reduces creep. Some ODS-Al alloys show excellent creep behavior and strength at temperatues up to 300°C. However, drawback of these alloys is the reduced room temperature ductility and damage tolerance. Nevertheless, ODS-Al alloys are excellent candidates for light weight structures for elevated operation temperatures. More research work is necessary to increase the operation temperature of now 50% of the alloy´s solidus temperature up to 90%.

ODS-variants of Ni-base alloys and Fe-base alloys feature operation temperatures up to 90% of their solidus temperature without creeping. However, Ni-base alloys need oxidation protection coatings at temperatures exceeding 1000°C. Fe-base, ferritic alloys show the superior oxidation behavior up to 1250°C but lower admissible loads compared to Ni-base ODS. Nevertheless, both types of ODS-alloys posess a high potential for the improvement of the efficiency of thermal engines. The drawback for high temperature applications is the limited design potential compared to cast components due to the mechanical alloying and PM/HIP route. Nevertheless, the Fe-base alloy PM2000 is now used for serial high temperature components of automotive engines. Research work is continued in order to improve processing and material properties.

7 Conclusions

The results of the study show that there are a lot of research activities in the fields of metal alloys in order to improve the ecological situation of man-made technology. However, driving forces of these developments are a mixture of political, economical and ecological factors. Main research and development domains are the reduction of weight for transportation systems on ground and in air, the increase of efficiency of thermal engines for transport or current generation and the reduction of energy and raw materials consumption in industrial production. However, improved technical components do not only need generally improved materials. With increasing technical demands for the components, tailor made materials for the special applications are necessary. In general materials do not meet all the requirements of the special technical solution. The higher the requirements, the more diversified the materials properties have to be. Besides standard solutions like alloying, new processes exceeding the limits of thermodynamical equilibrium such as supersaturation of alloys by rapid solidifications are investiagted in order to get new alloys with new properties. An example is the Li-supersaturated AlLi-alloy with decreased specific weight. On the other hand, more complex loads like the combination of thermal, mechnical and chemical load in addition to the light-weight demand lead to the necessity of special designed materials compounds consisting of different materials types. However, the combination of different materials often produces drawbacks in materials properties and processing. E.g. oxide dispersion strengthening improves the creep behaviour at elevated or high temperatures, but deteriorates room-temperature properties. Metal matrix composites (MMC) exhibit higher stiffness and thus an advantage in weight, but low fracture toughness and damage tolerance. Ductile phase toughening of brittle aluminides is only metastable du to the thermodynamical instability of the metal second phases at high temperatures.

In some cases, material combination counteracts the demands for recycling due to the problems in materials separation. For a global ecological effect of the technical components produced, this fact must be carefully taken into account.

Besides the problems in combining different types of materials, the process of materials combination is more complex compared to cast and wrought alloys. The production of ODS-alloys for instance consists of high energetic milling of the matrix alloy and the oxides with subsequent hot isostatic pressing and extrusion. This means a cost, time and energy intensive production process. That could in fact counteract the aimed effect of the technical solution for improved environmental compatibility. On the other hand, too high materials or product costs affect the competitivness.

The above-mentioned results show, that in many cases an appropriate materials solution for the respective technical problem can be achieved in long term. However, the effect of this special technical solution on fuel saving and thus on the decrease in reagents emission or raw materials consumption must be carefully compared to the energy and materials consumption during production process. For a global estimation of the effect of technical solutions with improved materials a calculation of all energy and mass fluxes, beginning at the raw materials mining and transportation to the complete production process is undoubtly necessary.

References

1 Bild der Wissenschaft, DVA, 2/1994, p. 68, in German

2 NATURE, Vol 374, april 1995, p. 487

3 Süddeutsche Zeitung, Süddeutscher Verlag, 4/8/95, in German

4 Daimler-Benz HighTechReport 4 / 1994

5 Daimler-Benz HighTechReport 4 / 1994

6 Thomas J. Ruden and Darryl L. Albright - Magnesium Castings for Auto Applications - Advanced Materials & Processes 6/94 S. 28 - 32

7 Technical Note - Advanced materials and processes 4/95, p. 10

8 Alfred Frisch - Zukunft der NE-Metalle in der Automobilindustrie - Metall 3/95 p. 166 - 167

9 A. Koewius - Aluminium, Automobil und Recycling - einige grundsätzliche Aspekte Aluminium 3/95 S.276 - 281

10 M. Peters und W.A. Kayser - Das Potential metallischer Leichtbauwerkstoffe in der Luft- und Raumfahrt - VDI Berichte nr.1080, 1994, s. 483 - 506 Werkstofftag 1994, VDI-Gesellschaft Werkstofftechnik

11 J.C. Ekvall, J.E. Rhodes, G.G. Wald - Methodology for evaluating weight savings from basic material properties - Design fo fatigue and fracture resistant structures, p. 328-341, ASTM-STP 761, ASTM Philadelphia, 1982

12 E.Loechelt - Übersichtsvortrag: Leichtbau in der Luft- und Raumfahrt - VDI Berichte nr.1080, 1994, s. 461 - 471 Werkstofftag 1994, VDI-Gesellschaft Werkstofftechnik

13 Technical Note - Advanced Materials & Processes , 8/94 p. 9

14 B. Reuter- Diplomarbeit - Metallische Verbundwerkstoffe mit Aluminium-Matrix", 1989

15 Information on the TMCTECC Program - Contact: Fred Polhemus, United Tech. Corp. Pratt &Whittney, West Palm Beach, USA 1994

16 Product Information on aluminium composites - 3M, 1995

17 Sick G., Essig G - Aluminium, 67. Jahrgang 1991, 9, S 880, in German

18 Schmid E.E- 2. Symposinum Materialforschung des Bundesministeriums für Forschung und Technologie, Projektträgerschaft Material- und Rohstofforschung (PLR),S 899, 1991, in German

19 Kumpfert J. et al - Proceedings of the 7th World Conference on Titanium, San Diego, USA 1992

20 Bartels et al - Proceedings of the 13th international Plansee Seminar 1993, Vol.3, pp 564 ff

21 Hedrich H.D - VDI Berichte Nr. 600.4, 1987, S 401, VDI-Verlag, in German

22 Campo E. and Lupinc V.- in "Innovative Materials, Prospects and Problems in a Competitive Industrial Context", Edited by P. Vincenzini, Techna Srl, 1993

23 Singer R.F - VDI-Bericht Nr. 1151, 1995, VDI-Verlag, in German

24 Smarlsky W., Sinheiser L.- VDI Berichte Nr. 1151, 1995, VDI-Verlag, in German

25 E.Arzt -2. Symposinum Materialforschung des Bundesministeriums für Forschung und Technologie, Projektträgerschaft Material- und Rohstofforschung (PLR), S 103, 1991, in German

26 R. Bruno - Innovative Materials edited by P. Vincenzini, Techna Srl, 1993

27 C. Hendricks - VDI Berichte Nr. 1080, 1994, p. 3-16, VDI-Verlag, in German

28 L. Hamm - International Iron and steel Institute, Brussels, 1993

29 B. Engl und E.-J. Drewes - VDI Berichte Nr. 1080, 1994, p. 35-54, VDI-Verlag, in German

30 W. Bleck, K. Blümel and W. Prange -VDI Berichte Nr. 1080, 1994, p. 25-34, VDI-Verlag, in German

31 D. Stark-Seuken, W. Bleck und W. Dahl - VDI-Berichte Nr. 1151, 1995, p. 503-513, VDI-Verlag Deutschland, in German

32 W. Prange, C. Schneider - VDI-Berichte Nr.1021, 1993, p. 45-52, VDI-Verlag, in German

33 R.F. Singer in D. Coutsouradis et al. (editors), Materials of Advanced Power Engineering, Part II, Kluwer Academic Publishers, Dordrecht 1994, S. 1707-29

34 Lipsitt H.A. et al. - Metal Transactions A, Vol 6A (1975), pp 1991-1996

35 Tuominen S. and Wojcik C. - Advanced Materials and Processes, Vol 147, No. 4, April 1995, p. 23-26

36 Sauthoff G - 2. Symposinum Materialforschung des Bundesministeriums für Forschung und Technologie, Projektträgerschaft Material- und Rohstofforschung (PLR),S 877, 1991, in German

37 Peters M., Winkler P.-J. - Metall, 46. Jahrgang, Heft 12, Dec. 1992

38 U. Herold-Schmidt, S. Schwantes, G. Broden - Advanced Materials and Structures from Research to Application, edited by J. Brandt et al., SAMPE European Chapter 1992

39 Sauthoff G., Intermetallische Phasen, in: Symposium Materialforschung 1988, KFA-PLR Jülich 1988, S.399-414

40 Rudy M., Sauthoff G., Creep behaviour of the ordered intemetallic (Fe,Ni)Al phase, in: High-temperature ordered intermetallic alloys, C.C. Koch, C.T. Liu and N.S. Toloff, MRS, Pittsburgh 1985, p.327-333

41 Walter J.L. and Cline H.E. - Metallurgical Transactions 1 (1970) 1221-1229

42 Sauthoff G. und Kleinekathöfer W. - VDI Bericht Nr. 1151, VDI-Verlag 1995, in German

44 Beer St., Frommeyer G., Schmidt E. und Helbig H. - VDI-Berichte Nr. 1080, 1994, p89, VDI-Verlag, in German

45 F. Jansen, E. Lugscheider - VDI-Berichte Nr. 1151, 1995, VDI-Verlag, in German

46 R. Scholl, B. Kieback - Proceedings of the PM Worl Conference, Vol. 2, 1994, Paris

47 Publication Raufoss

48 Jangg G., Kutner F., Korb G.; Aluminium, 51, 1975, 641

49 Jangg G., Kutner F., Korb G., Powder Metall. Int., 9(1), 1977,24

50 Hummert Klaus, PEAK Werkstoff GmbH, Germany, in German

51 J.D. Whittenberger, R.K. Viswanadham, S.K. Mannan, K.S. Kumar -Journal of Materials Research 4, 1989, p. 1164

52 R.S. Polvani, Wen-Shian Tzeng and P.R. Strutt, Metal Transactions A, 7A (1976), p. 33

53 K. Zöltzer - Proceedings of the 13th International Plansee Seminar, Eds H. Bildstein and R. Eck, Metallwerke Plansee, Reutte (1993), Vol. 3, p. 528-536

54 Korb G. et al. -Proceedings of the 13th International Plansee Seminar 1993, Vol.1, pp 130 ff

55 N. Wood, Q. Mabbutt, J. Wonsowski and F. Starr - The long-term oxidation behaviour of iron based ODS-alloys - Proceedings of the 13th International Plansee Seminar 1993, Vol.1, pp 115 ff

56 Advanced Materials and Processes 7/94, Vol. 146, No.1, p.7, ASM International

57 M. Peters und W.A. Kayser - Das Potential metallischer Leichtbauwerkstoffe in der Luft- und Raumfahrt - VDI Berichte nr.1080, 1994, s. 483 - 506 Werkstofftag 1994, VDI-Gesellschaft Werkstofftechnik

58 Donald Webster - Advanced Materials & Processes 5/94pp. 18ff

59 Thomas B. Gurganus - Aluminium Powder Applications - Advanced Materials & Processes, 8/1995, p. 57-59

60 D.L. Albright, T. Ruden - Magnesium utilization in the north american automotive industry - Hydro Magnesium 4/1994

61 N. Zeumer, Dr. H. Fuchs - Einsatz von Aluminium- und Magnesiumguß im Leichtbau VDI Berichte Nr. 1021, 1993 p. 241-254

62 H. Grabert - Magnesium: das leichte Leichtmetall - technik heute 3/1979 p. 1 - 11

63 Carl Zweben - Materials engineering 2000 and beyond: Metal Matrix Composites - Advanced Materials & Processes 1/1994 p. 28-30

64 B. Reuter - Diplomarbeit "Metallische Verbundwerkstoffe mit Aluminium-Matrix", 1989

65 Rainer Rauh - Dissertation "Einsatzpotential und Beanspruchungsgrenzen partikelverstärkter Aluminiumlegierungen auf der Basis einer metallkundlichen Bewertung", S. 6ff

66 B36 J.A. Black - Shaping Reinforcements for Composites, Advanced Materials and Processes, 19888, Metall Process 3

67 Technical Note - Aluminium 4/95 p 420-421

68 R. Mehrabian, F.M. Hosking, F.F. Portillo, R. Wunderlin - Structure and deformation characteristics of rheocast metals - Dep. of metallurgy and mining engineering, Univ. of Illinois, Final report DAAG46-76-C-0046

69 M.F. Ashby - Materials Selector Data -

70 Product Information on titanium composites - 3M, 1995

71 MEL Product Information, 1995

72 John Busch - Materials compete in recycling alternatives; 1 / 1995; Advanced materials & processes, p. 25-26

73 Liedke Christa - Wuppertal-Institut, in Bild der Wissenschaft, 9/1995, Deutsche Verlagsanstalt GmbH, S. 27, in German

Tables

Hothouse gases	**Ejection of hothouse gases**	**Mean existence time**	**Share in additional hothouse effect in %**	**relative hothouse potential***
Carbondioxid CO_2	Fire clearing of tropical rain forest, combustion of fossile energy resources (heating, traffic)	50 - 200 years	50	1
Methan CH_4	Fire clearing of tropical rain forest, rice fields, dumps	10 yeras	13	58
Ozon O_3	traffic	2 -3 months	7	1800
Dinitrogenoxide N_2O	manure, combustion of fossile energy resources	130 - 150 yeras	5	206
FCCH CCl_3F	fuel gas	65 years	5	3970

* compared to an equivalent mass of CO_2 in kg

Source: Bild der Wissenschaft, DVA, 2/1994, p68

Table 1: Greenhouse reagents and sources

	R_m (MPa)	$R_{p\ 0,2}$ (MPa)	$R_{d\ 0,2}$ (MPa)	A_5 (%)	K_C (MPa$\sqrt{m}$)	SRK (MPa)	Dichte (g/cm^3)
7075 T7351	490	390	400	7	-	290	2,80
7075 T7651	490	415	435	6	-	172	2,80
7075 T651	525	476	455	7	28	69	2,80
7050 T7651	525	455	440	9	28	172	2,82
7150 T6151	580	540	530	9	22	69	2,82
7150 T651	570	525	-	8	-	-	2,82
7150 T7751	580	540	530	8	22	172	2,82
7055 T7751	615	595	594	7	24	103	2,85

Table 2: Typical properties of 7xxx (AlZn-based) series alloys

2xxx alloys 2024, 2324, 2224		7xxx alloys 7075, 7475, 7050/7010, 7150	
fuselage	planking stringer ribs	fuselage	extruded stringer milled ribs seat components window frames
wing	planking/stringer (bottom side) slat	wing	planking/stringer (top side) ribs girders

Table 3: Typical application fields of 2xxx and 7xxx series alloys in aircraft

Component	**Intermetallic**	**Temperature**
High-pressure compressor		
• housings	TiAl	650°C
	Ti3Al	600°C
• blades	TiAl	700°C
Combustion chamber		
• housings	TiAl	750°C
• shingles	NiAl	1300°C
	$MoSi_2$	1600°C
High-pressure turbine		
• gaskets	NiAl	900°C
• liner	NiAl	900°C
• vanes	NiAl	1300°C
	$MoSi_2$	1400°C
Low-pressure turbine		
• housings	TiAl	750°C
• blades	TiAl	750°C
	NiAl	900°C

Table 4: Applications of intermetallics in gas turbines

<table>
<tr><th colspan="7">alloying elements in wt%</th></tr>
<tr><th>C</th><th>N</th><th>Mn</th><th>P</th><th>Al</th><th>Nb</th><th>V</th></tr>
<tr><td>0,07</td><td>0,006</td><td>1,3</td><td>0,01</td><td>0,04</td><td>0,045</td><td>0,045</td></tr>
<tr><th colspan="7">mechanical properties</th></tr>
<tr><td colspan="2">YS</td><td colspan="3">UTS</td><td colspan="2">e_{80}</td></tr>
<tr><td colspan="2">612</td><td colspan="3">671</td><td colspan="2">25</td></tr>
</table>

Table 5: Chemical composition and properties of a hot-rolled, micro-alloyed high-strength steel (QStE500TM)

elements in wt%							
C	Si	Mn	P	S	Al	Cu	Fe
0,008	0,02	0,22	0,047	0,008	0,064	0,01	bal

Table 6: Chemical composition of bake-hardening steel ZStE 180 BH

alloying elements				
Al	Si	Fe	C	O
bal.	12-20	0-5	0.5-4	0.5

Table 7: Variation of alloying elements in dispersion strengthened aluminium alloys

Alloy Type	AA No.	Specific Property
Al-Cu-X	2024, 2014, 2090, 2091, 2219, 2618	Damage-tolerant, Al-Li, Creep-resistant
Al-Mg-X	5091	MA (AL-905XL)
Al-Mg-Si-X	6013, 6061	Corrosion-resistant
Al-Zn-X	7075, 7475, 7010, 7050, 7055	High-strength
Al-X	8009, 8019, 8090, 8091	Creep-Resistant (Powder Metallurgical), Al-Li

Table 8: Classification of High-strength Aluminium Alloys

Aluminum alloy, condition	7093, T-7E92	7075, T-6	7075, T-73	7050, T-74	7055, T-77
Room temp. properties, longitudinal direction					
Tensile strength, MPa (ksi)	607 (88)	572 (83)	503 (73)	517 (75)	593 (86)
Yield strength, MPa (ksi)	579 (84)	503 (73)	386 (56)	462 (67)	558 (81)
Elongation, %	14	11	13	15	11
Density, g/cm^3 (lb/in^3)	2.85 (0.103)	2.80 (0.101)	2.80 (0.101)	2.83 (0.102)	2.85 (0.103)
Specific tensile strength	854	821	723	735	835
Fracture toughness, $MPa{\cdot}m^{1/2}$ ($ksi{\cdot}in.^{1/2}$)	53 (48)	29 (26)	34 (31)	38 (35)	33 (30)
Modulus, GPa (Msi)	75(10.8)	72(10.4)	72(10.4)	72(10.4)	70(10.2)
Corrosion properties					
General[1]	A	C	A-B	B	B
Exfoliation[2]	P	EC	EA	EB	EB
Stress corrosion cracking, MPa (ksi)	>>310 (45)	55 (8)	276 (40)	241 (35)	207 (30)

1 — Ratings A through E are relative ratings in decreasing order of merit, based on exposure to sodium chloride solution by intermittent spraying or immersion.
2 — Accelerated exfoliation corrosion test per ASTM G34. P = pitting, least exfoliation; EA =superficial; EB = moderate; EC = severe; ED = very severe.

Table 9: Prealloyed P/M 7093 vs. ingot alloys

Material	Common Reinforcement Type	Approach
Aluminium & Magnesium	Particles Long-fibres Short-fibres	Stiffness, Strength, Wear-resistance (particles), Creep-resistance
Titanium	Long-fibres	High-temperature strength

Table 10: Overview of reinforced light-weight alloys

A: Type of Reinforcement	B: Production	C: Operating Condition
Particle material (e.g. Al_2O_3, SiC)	Raw material production, Solidification	Load type
Particle shape (e.g blocky, globulitic)	Hot-Working of the material (e.g extrusion, sintering)	Load direction
Particle size (typical: 10-30 µm)	Heat-treatment	Operating temperature
Particle volume content (typical: 10-20 vol.%)	Net-shape (e.g. forging, superplastic forming, mechanical machining)	Operating atmosphere
Particle size distribution (homogenity of the material)		

Table 11: Influencing Parameters on an Particulate Reinforced MMC´s Properties

Alloy, v/o SiC particulates, condition	X2080, 15v/o, T-4	X2080, 20v/o, T-4	6113, 25v/o, T-6
Tensile strength, MPa (ksi)	483 (70)	517 (75)	496 (72)
Yield strength, MPa (ksi)	365 (53)	393 (57)	437 (63.5)
Elongation, %	7.5	6	3
Density, g/cm^3 ($lb/in.^3$)	2.82 (0.102)	2.85 (0.103)	2.82 (0.102)
Modulus, GPa (Msi)	100 (14.5)	110 (16.0)	120 (17.5)
Coefficient of thermal expansion, $x10^6$	18	16	—
Thermal conductivity at R.T., W/m-°C	105	103.4	—

*Extrusions

Table 12: Typical properties of P/M MMC´s (extruded)

Figures

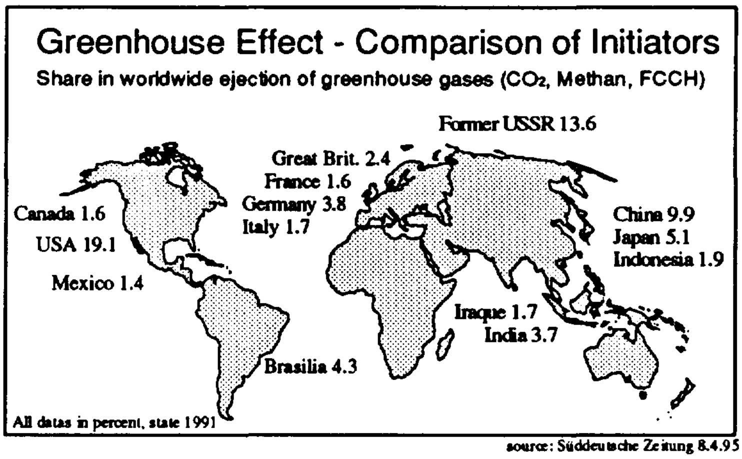


Figure 1: World wide initiators of green house gases

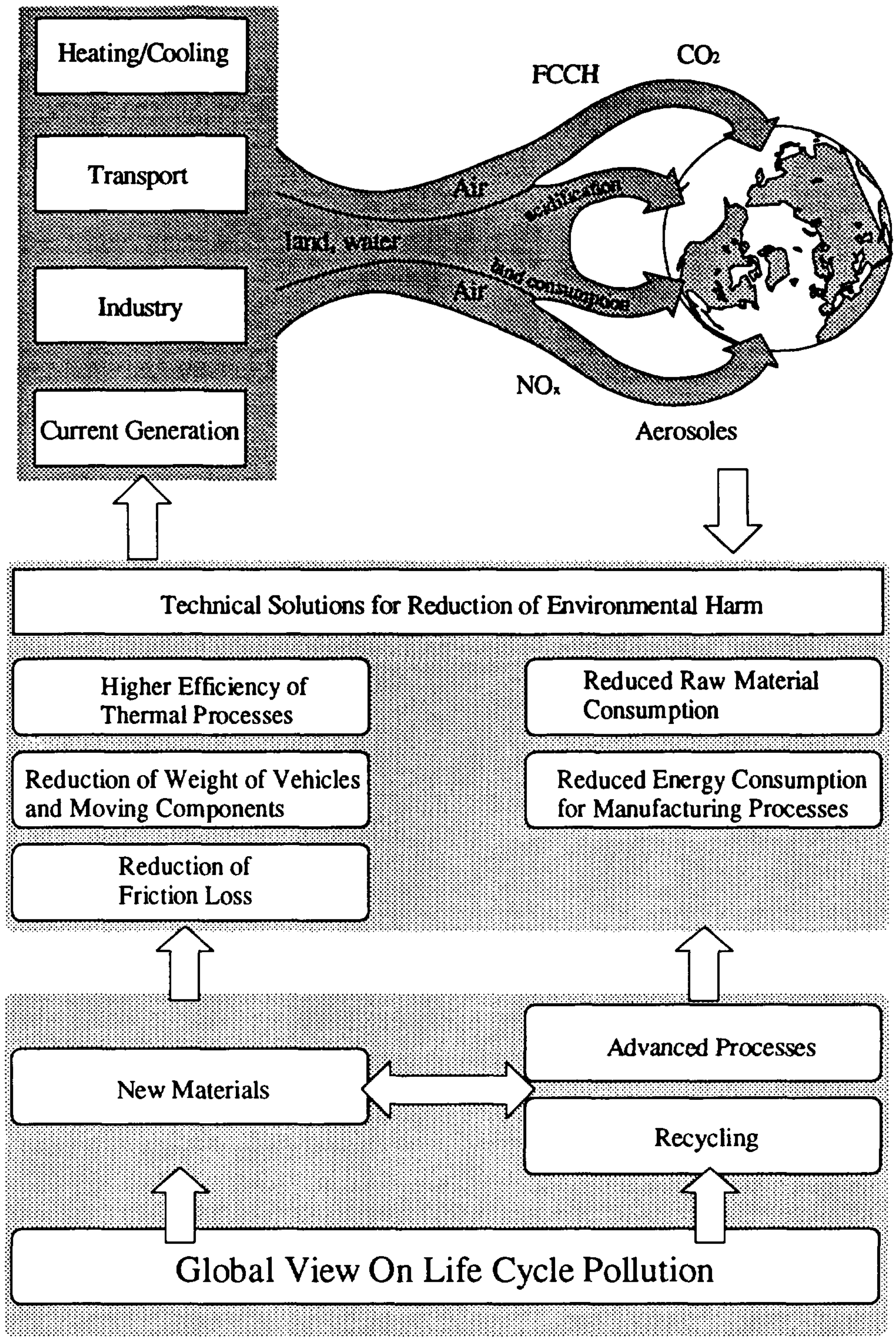


Figure 2: Factors for environmental harm and technical approaches for short or mean term solutions

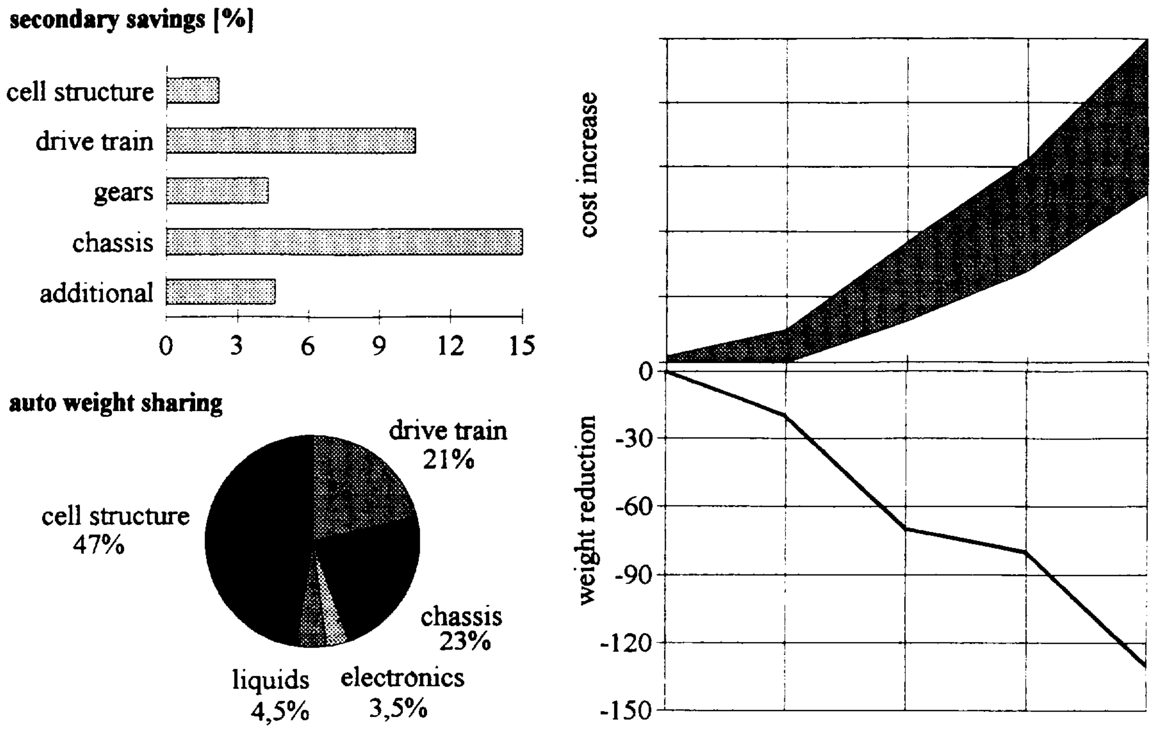


Figure 3: Reduction of weight and cost development

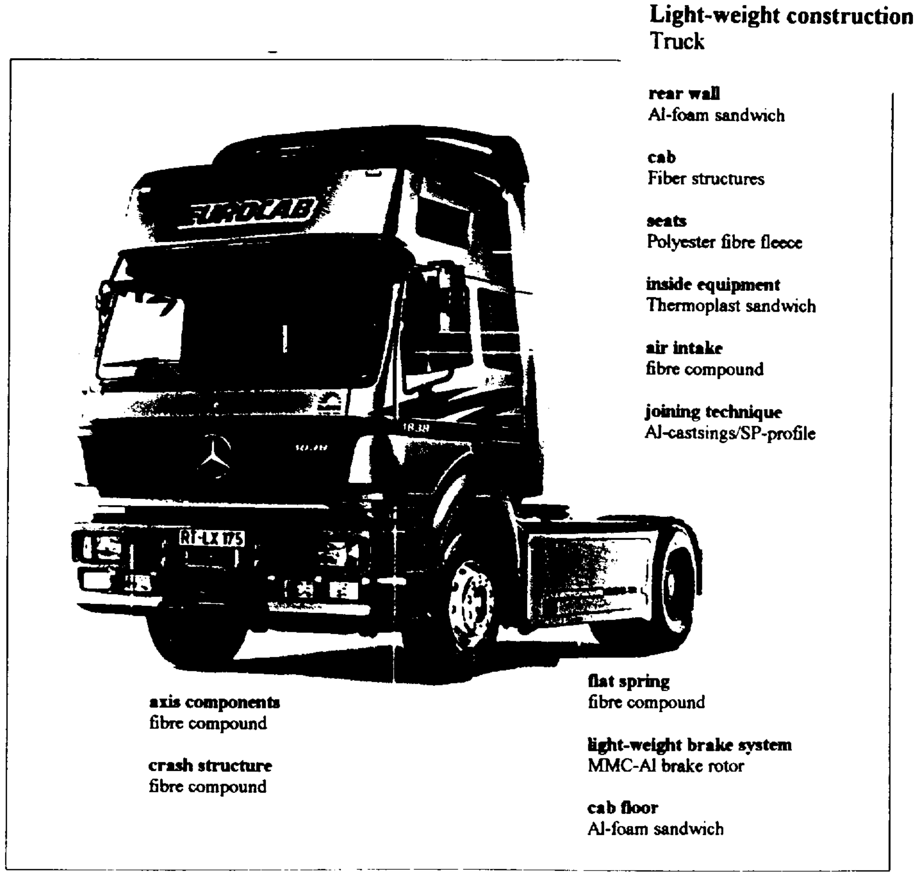


Figure 4: Light-weight construction concepts for a lorry

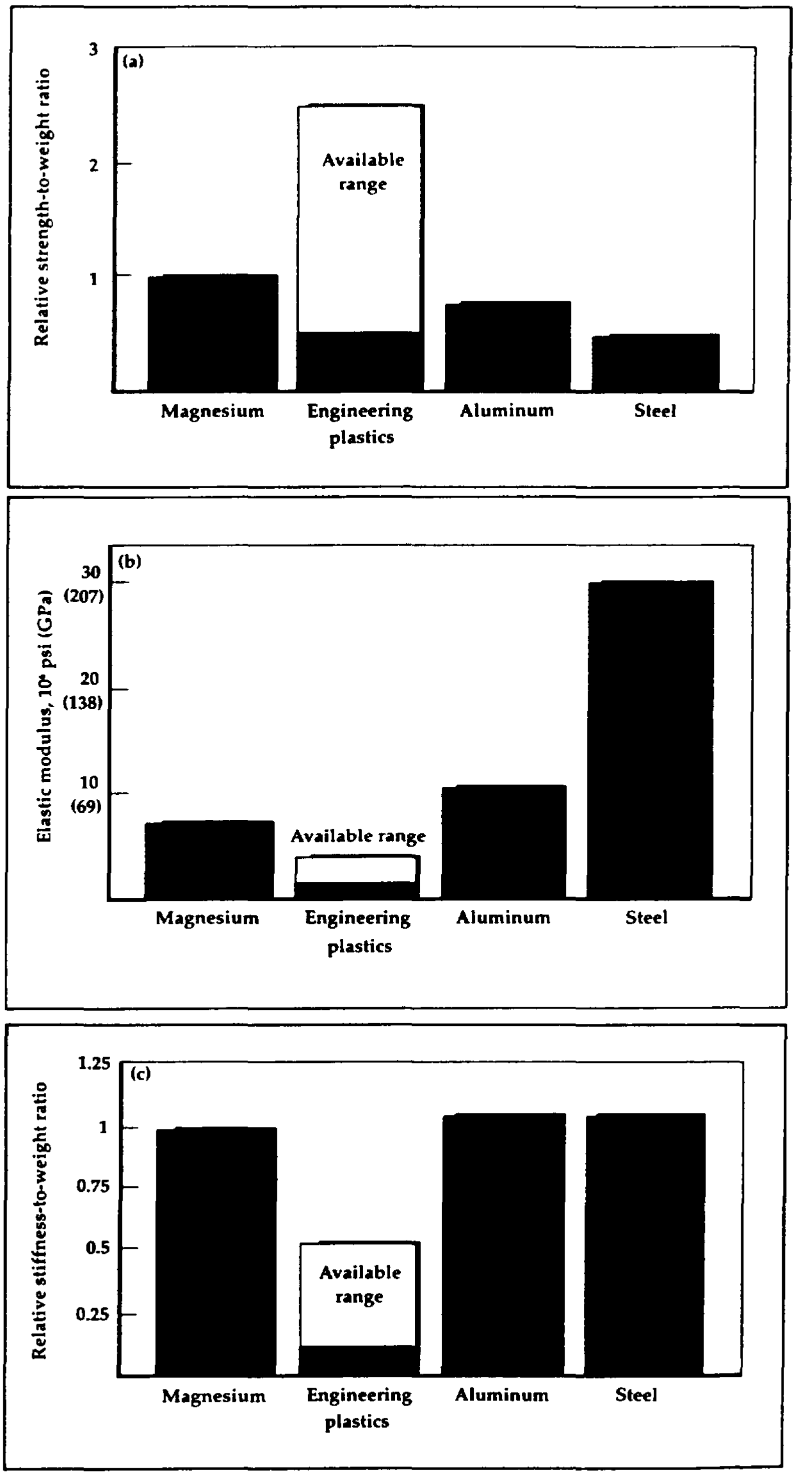
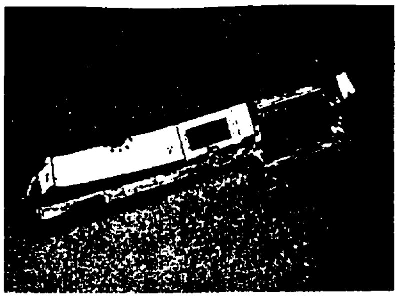
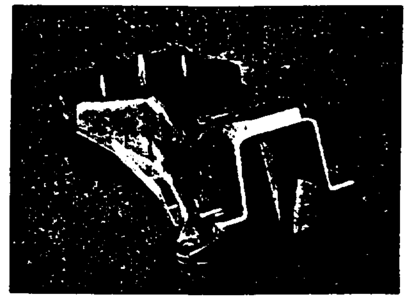


Figure 3: Property efficiency attributes of magnesium compared to those of selected other structural materials for auto applications. a) Relative strength-to-weight ratio. b) Eastic modulus. c) Relative stiffness-to-weight ratio.

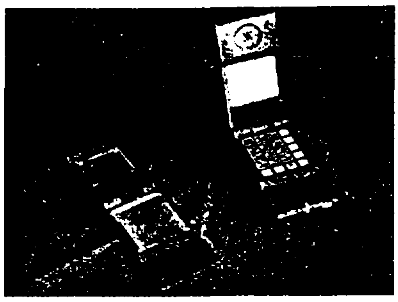
Knee Bolster Reinforcement Panel, AM60B



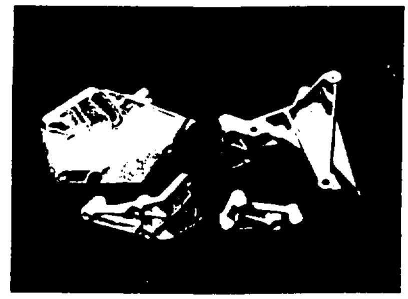
Steering Column Support Bracket, AZ91D



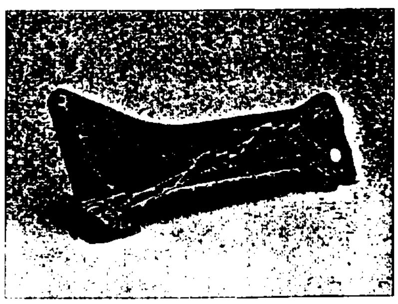
Cellular Telephone Housing, AZ91D



Engine Accessory Brackets, AZ91D



Bench Seat Stanchion, AM60B



Automotive Wheel, AM70

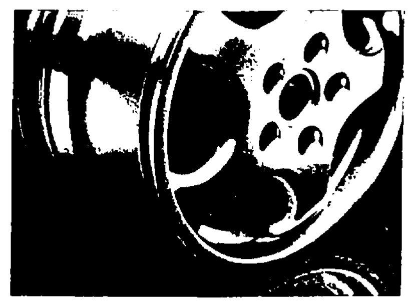


Figure 6: Typical magnesium applications

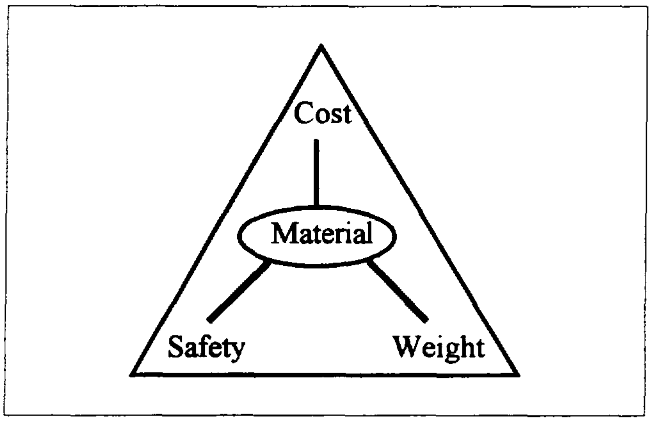


Fig. 7: Material choice in light-weight structures

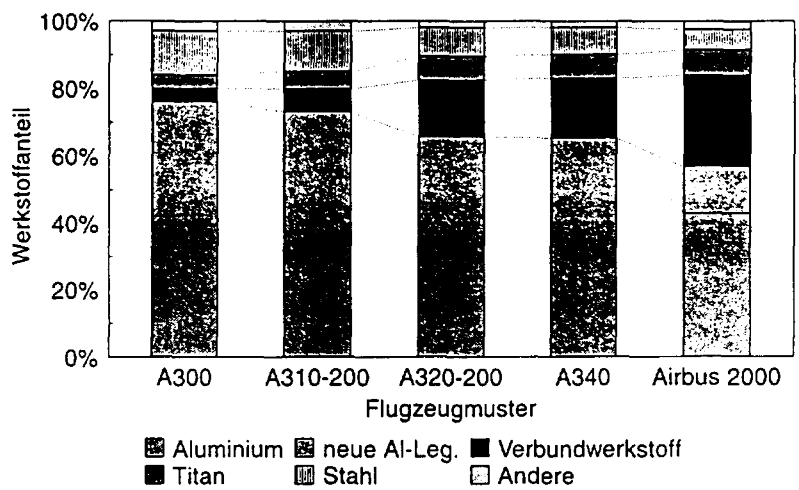
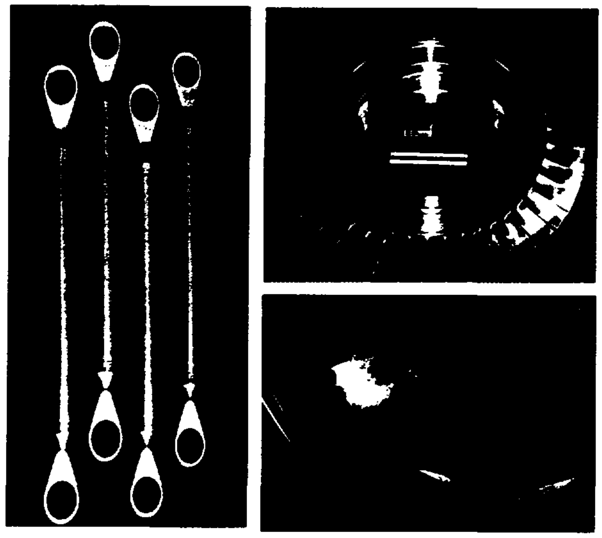


Figure 8: Content of different materials in aeroplanes



Nozzle, compressor and fan components

Figure 9: Components made by the use of long-fibre reinforced titanium

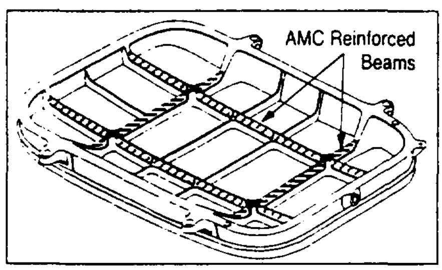


Figure 10: Aircraft panel- a typical appliction for long-fibre reinforced aluminium

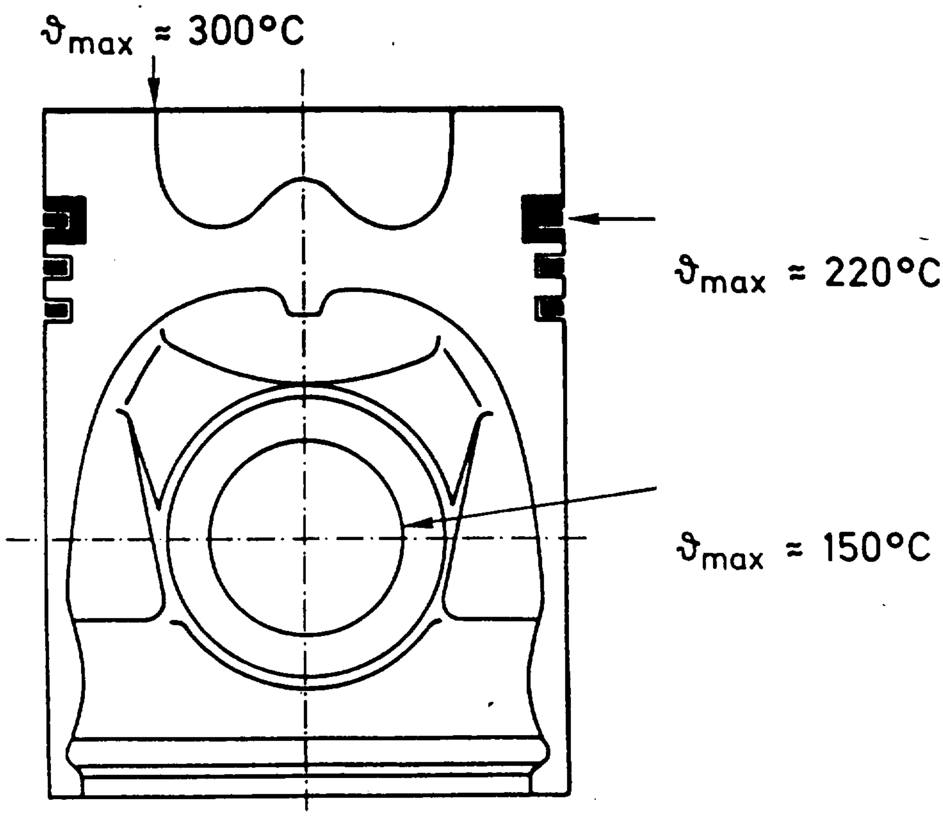


Figure 11: Critical piston sections [17]

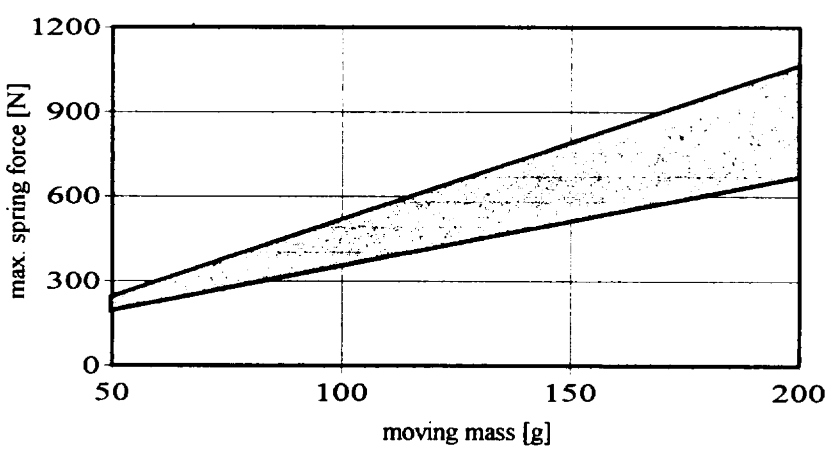


Figure 12: Required spring force of serial motors (related to the nominal rate of revolutions 6250 1/min) [20]

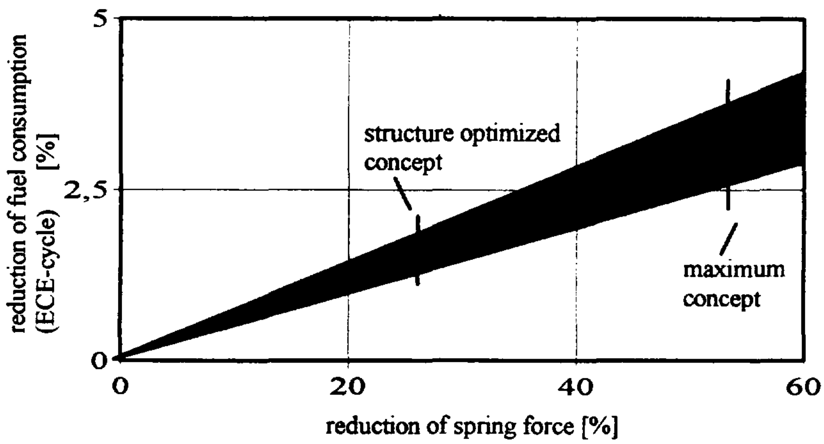


Figure 13: Reduction of fuel consumption with decreasing valve spring force (ECE-cycle) [20]

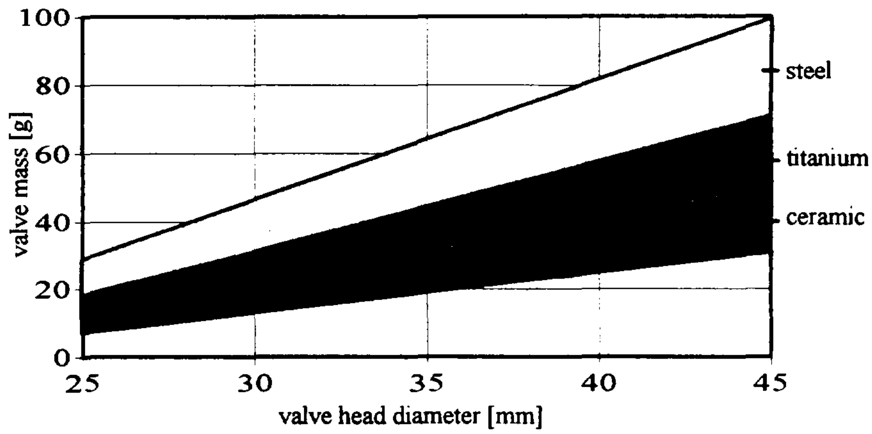


Figure 14: Masses of inlet valves [20]

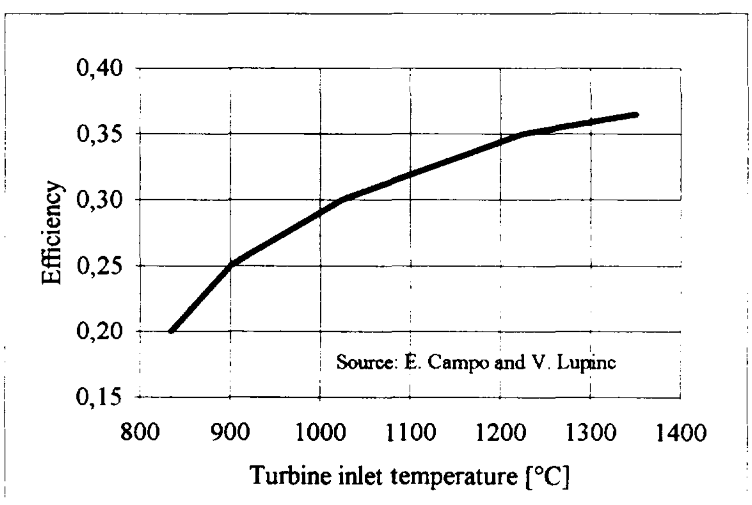


Figure 15: Increase in thermal efficiency with increasing gas temperature at turbine inlet [24]

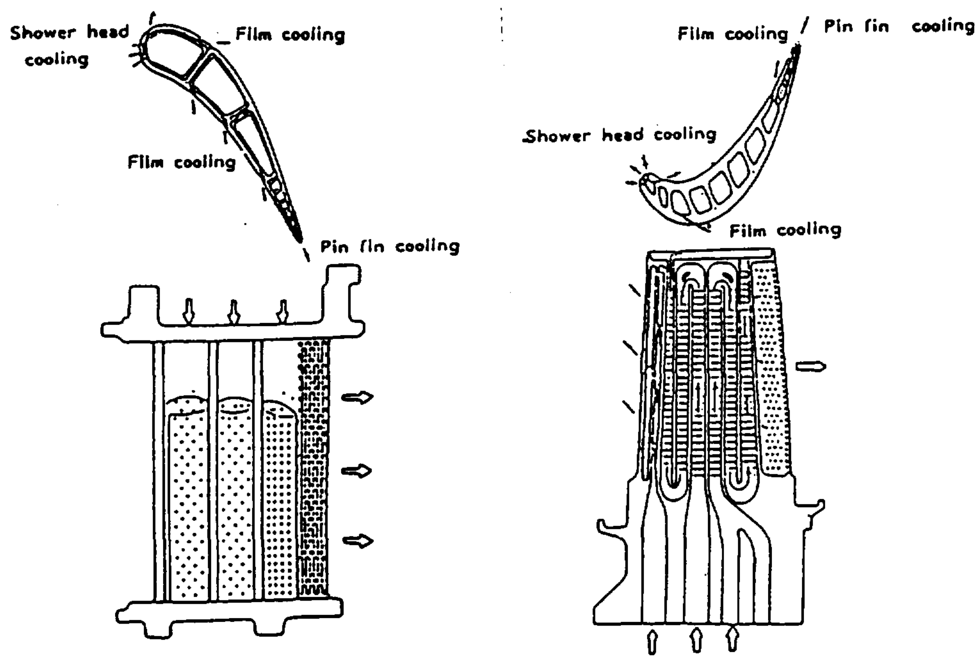


Figure 16: FMW 701F first stage airfoils geometry: a) nozzle guide vane and b) blade [24]

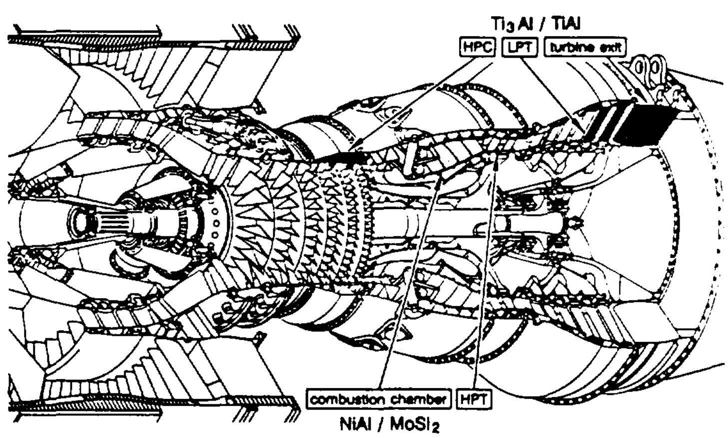


Figure 17: Application potential for intermetallic structural materials in gasturbines [24]

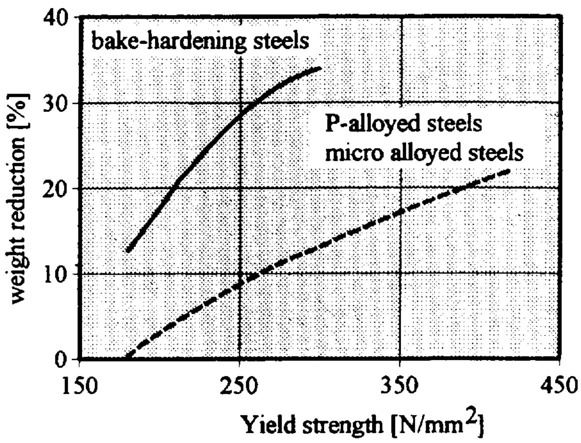


Figure 18: Weight reduction as a function of yield strength. Comparison between auto body structures (BH-steels) and crash elements (micro alloyed resp. P-alloyed steels) [32]

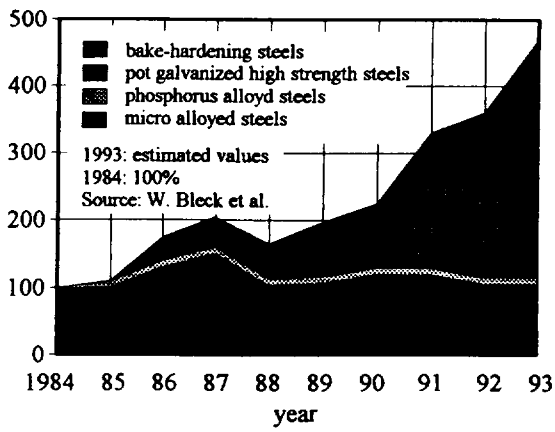


Figure 19: Increase in use of high strength steel strips in automotive industry [30]

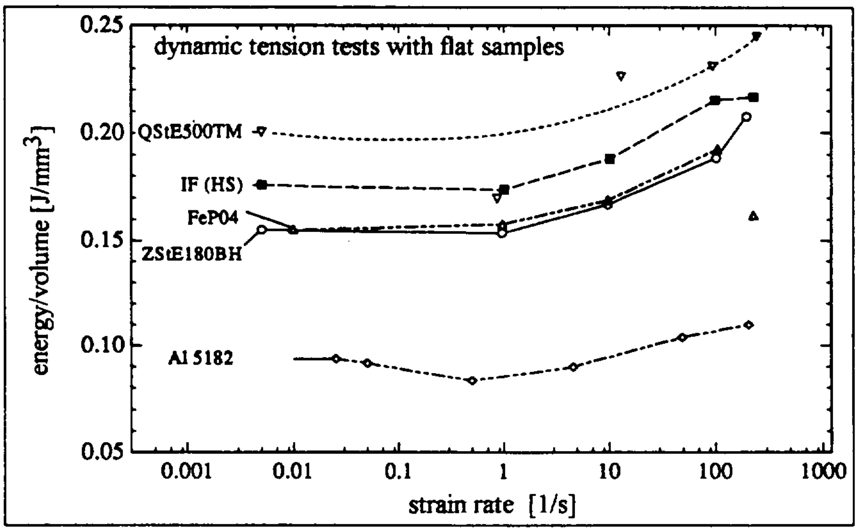


Figure 20: Dissipated specific energy of high strength steels during dynamic room temperature tests as a function of the strain rate [31]

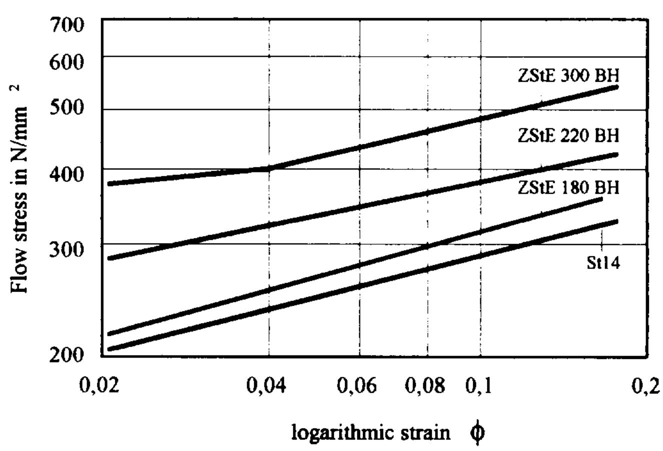


Figure 21: Flow stress of bake-hardening steels compared to steel St14 [30]

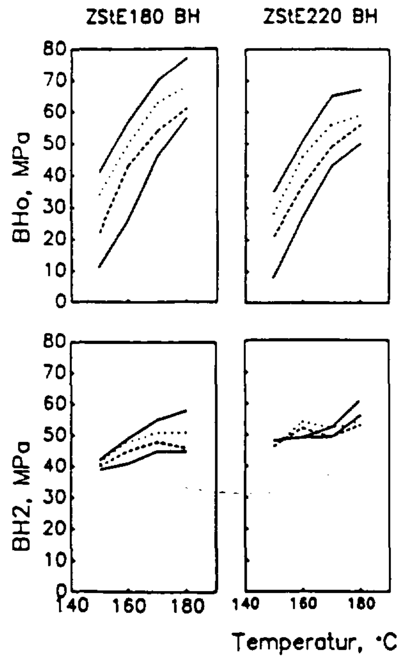


Figure 22: Influence of temperature and time on the bake hardening effect BH0 (without pre-deformation) and BH2 (2% pre-deformation) [29]

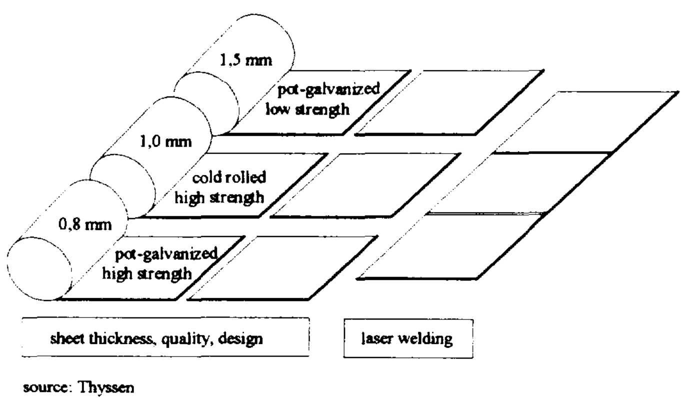


Figure 23: Schematic description of the production of tailored blanks [32]

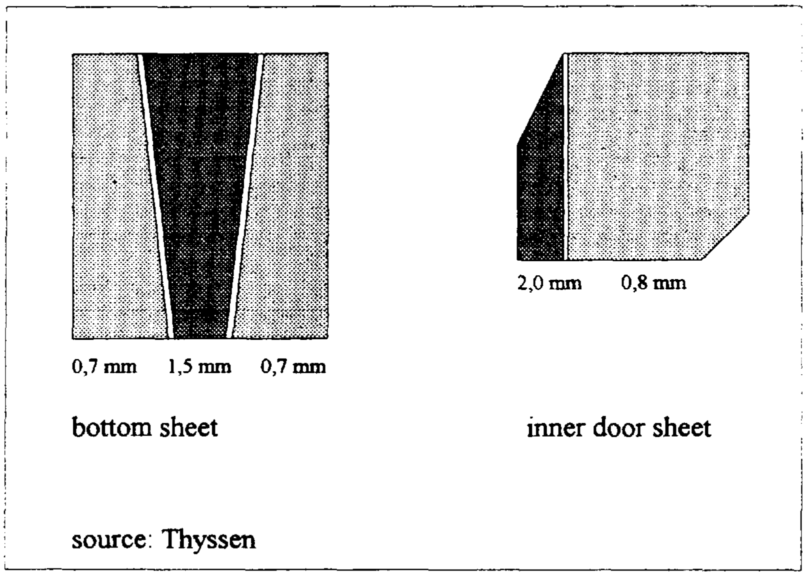


Figure 24: Examples of the design of tailored blanks [32]

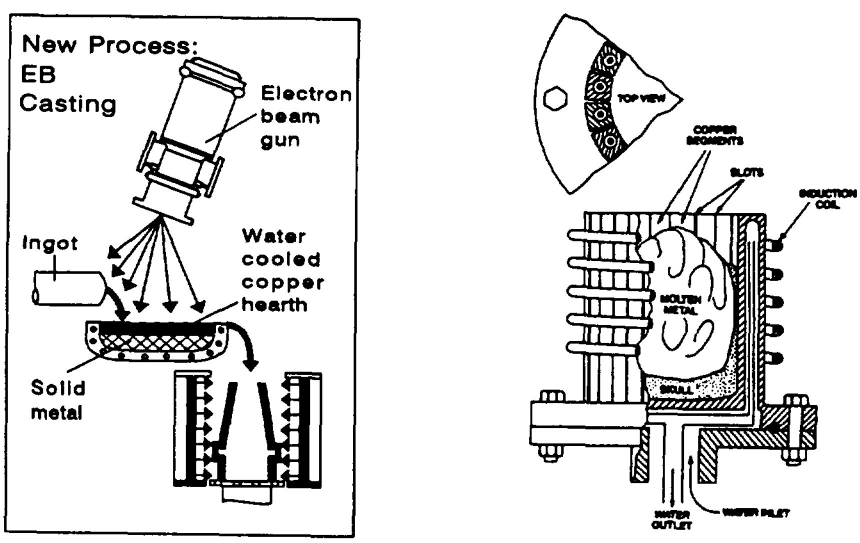


Figure 25: New casting processes: Current Induction Skull Crucible [23]

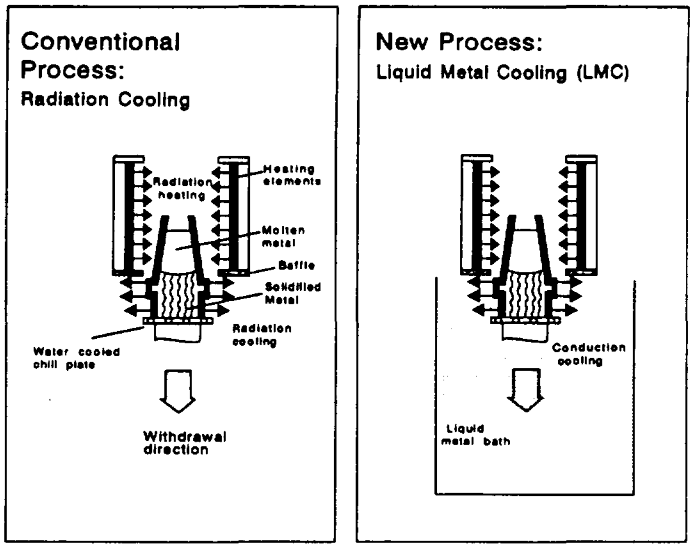


Figure 26: Comparison of conventional cooling and liquid metal cooling during directional and single crystal solidification [23]

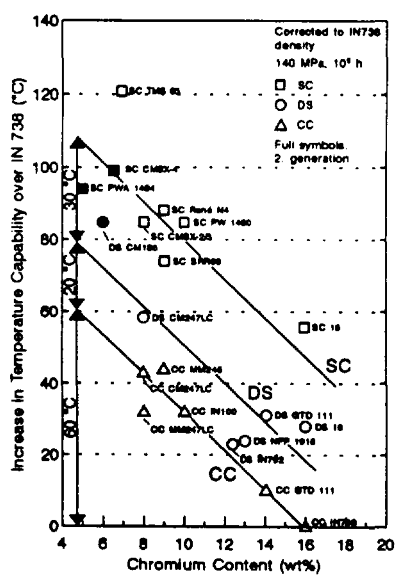


Figure 27: Maximum operation temperature of Ni-base alloys as a function of Cr-content. The temperatures are defined by creep resistance. The values are related to the creep strength of Ni-base alloy 738 [23/33]

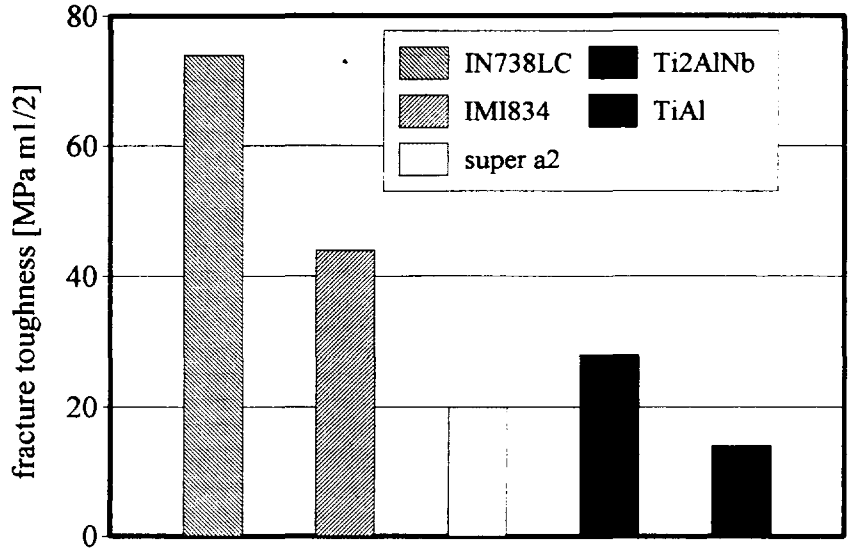


Figure 28: Room temperature fracture toughness K_{IC} of TiAl-alloys compared to Ni-base alloy IN738LC and Ti-alloy IMI834 [24]

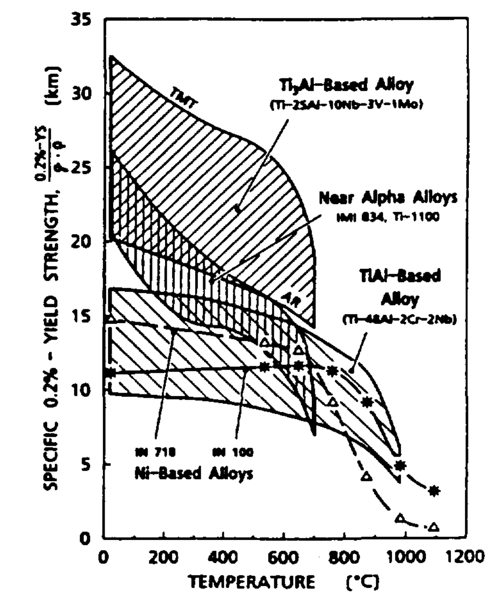


Figure 29: 0.2% yield strength of Ti_xAl as a function of temperature compared to conventional Ti- and Ni-base alloys [Kumpfert J. et al.]

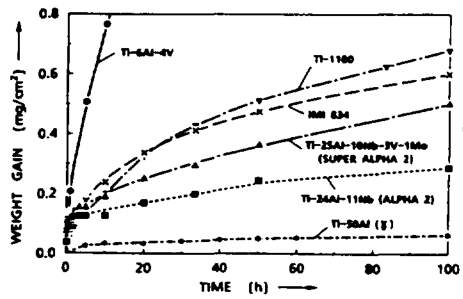


Figure 30: Oxidation behavior of titanium alloys [37]

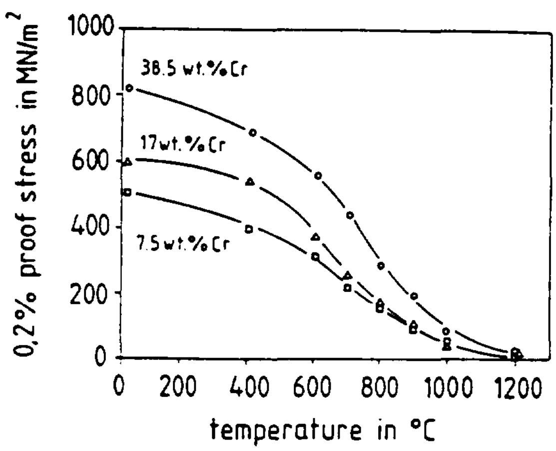


Figure 31: 0.2% proof stress of NiAlCr as a function of temperature and Cr-content [36]

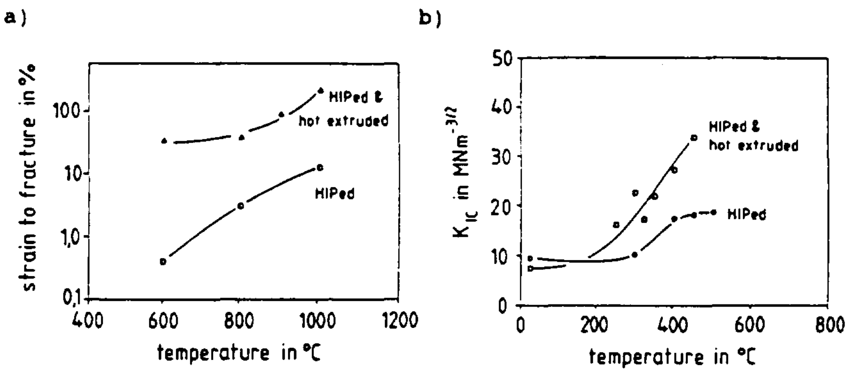


Figure 32: Temperature dependence of elongation and fracture toughness of NiAl-38,5Cr processed by HIP or HIP and extruding [36]

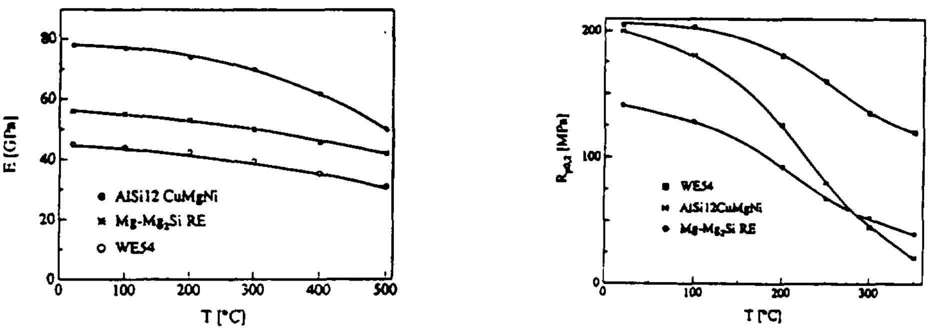


Figure 33: Youngs modulus and 0.2%-yield strength of $Mg-Mg_2Si$ as a function of temperature [44]

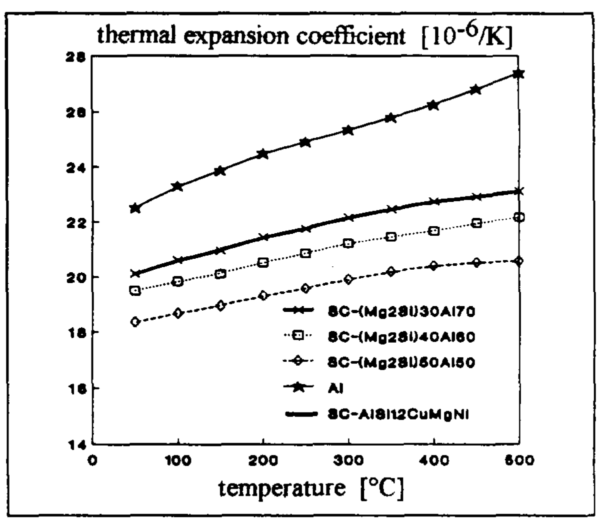


Figure 34: Coefficient of thermal expansion of different $Mg-Mg_2Si$ alloys as a function of temperature, compared to standard piston alloy [18]

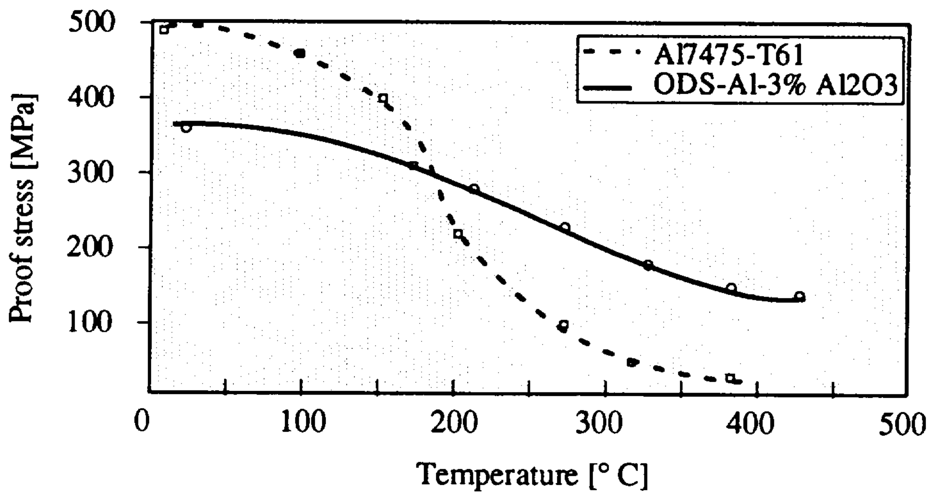


Figure 35: Proof stress of ODS-Al as a function of temperature, compared to Al7475 [Raufoss Inc., Norway]

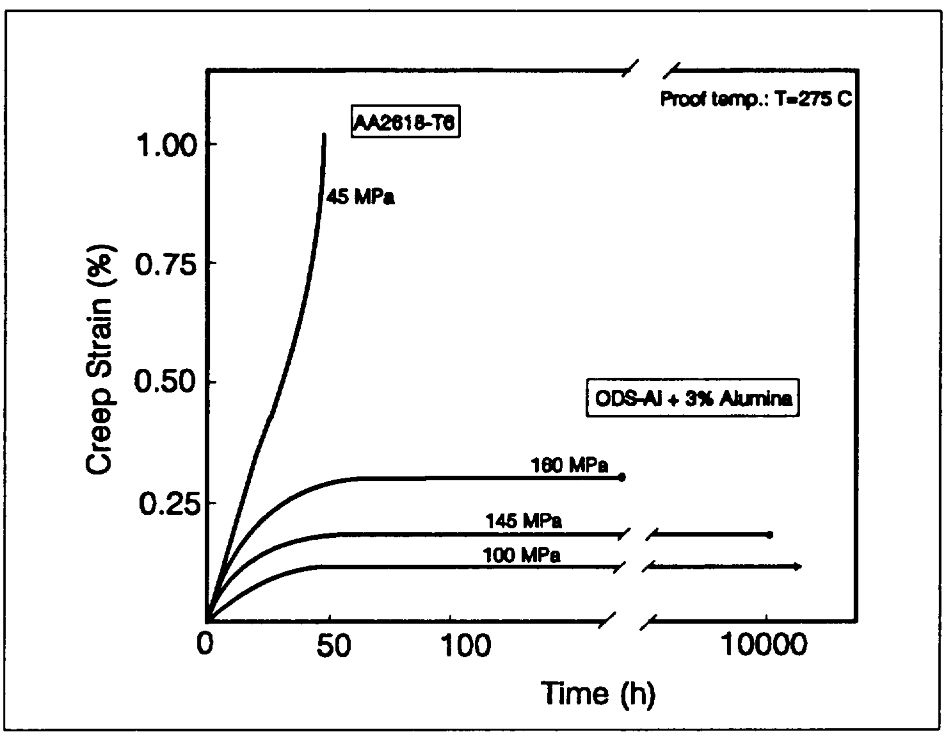


Figure 36: Creep behavior of ODS-Al (Al + 3% alumina) [Raufoss Inc., Norway]

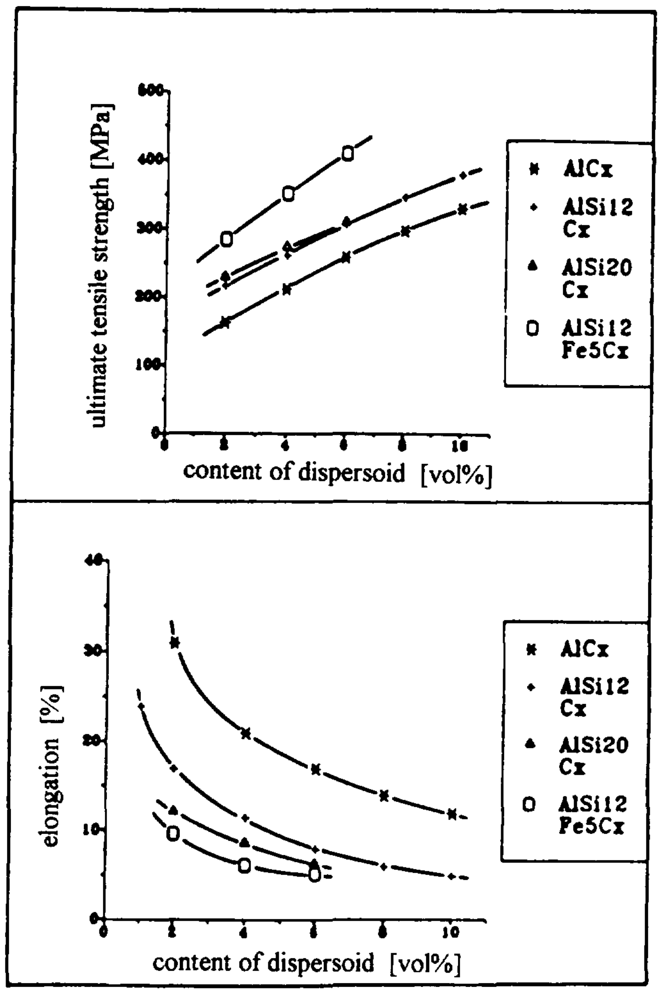


Figure 37: Ultimate tensile strength and elongation of different dispersion strengthend Al-alloys as a function of dispersoid content [50]

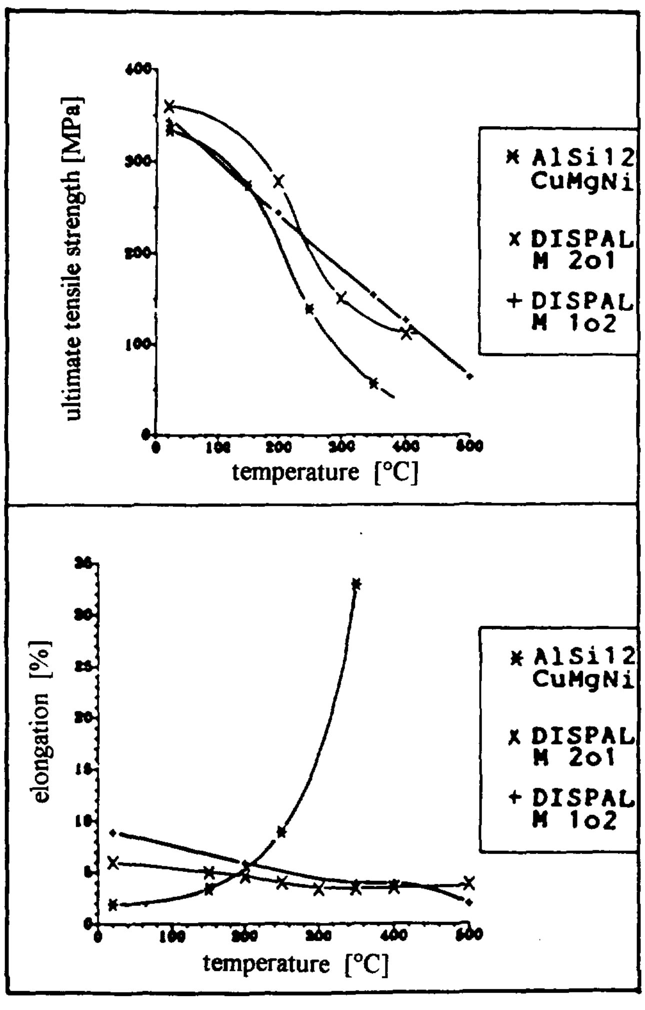


Figure 38: Ultimate tensile strength and elongation of different dispersion strengthend Al-alloys as a function of temperature [50]

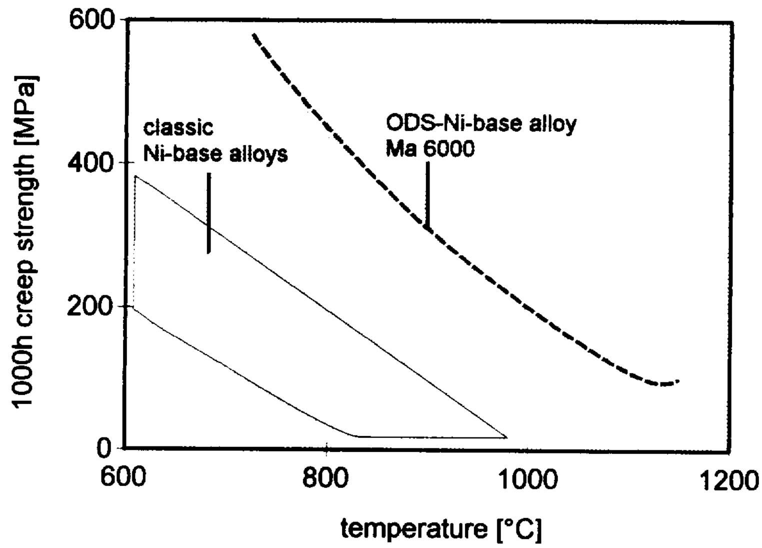


Figure 39: Creep behavior of ODS-Ni-base alloy MA6000 as afunction of temperature, compared to standard Ni-base alloys

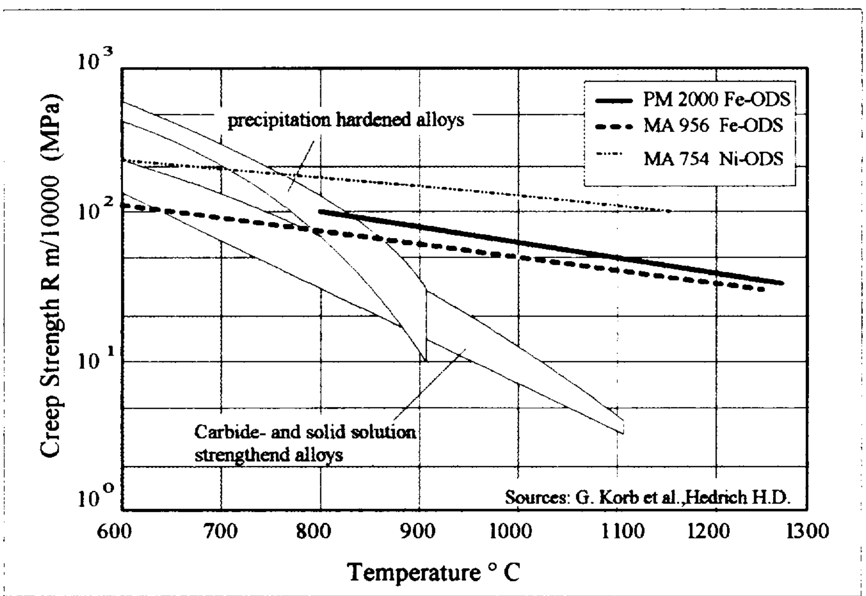


Figure 40: Creep behavior of ODS-Fe alloy PM2000 as a function of temperature, compared to standard high temperature alloys [54]

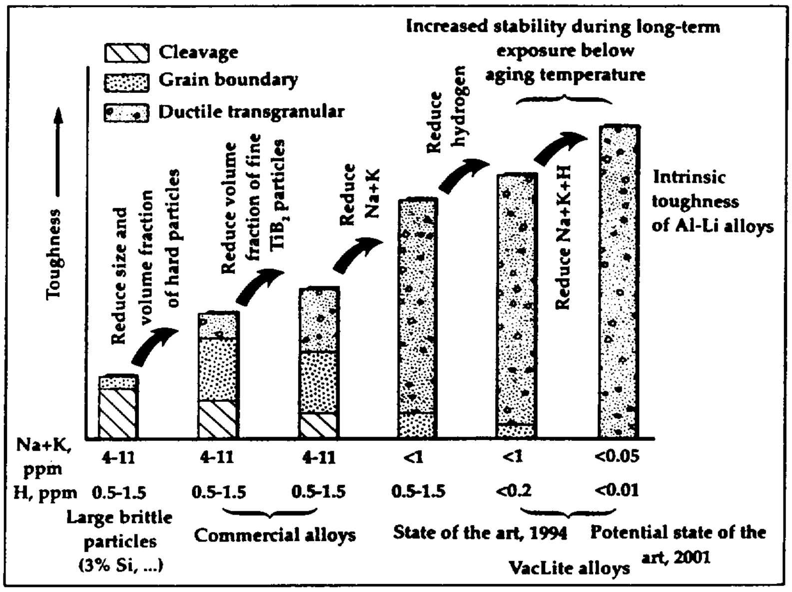


Figure 41: Increase of toughness as a function of the decrease of impurities for AlLi alloys

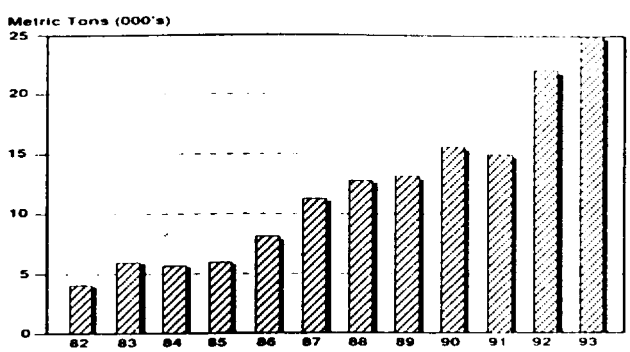


Figure 42: North American magnesium die-cast alloy consumption

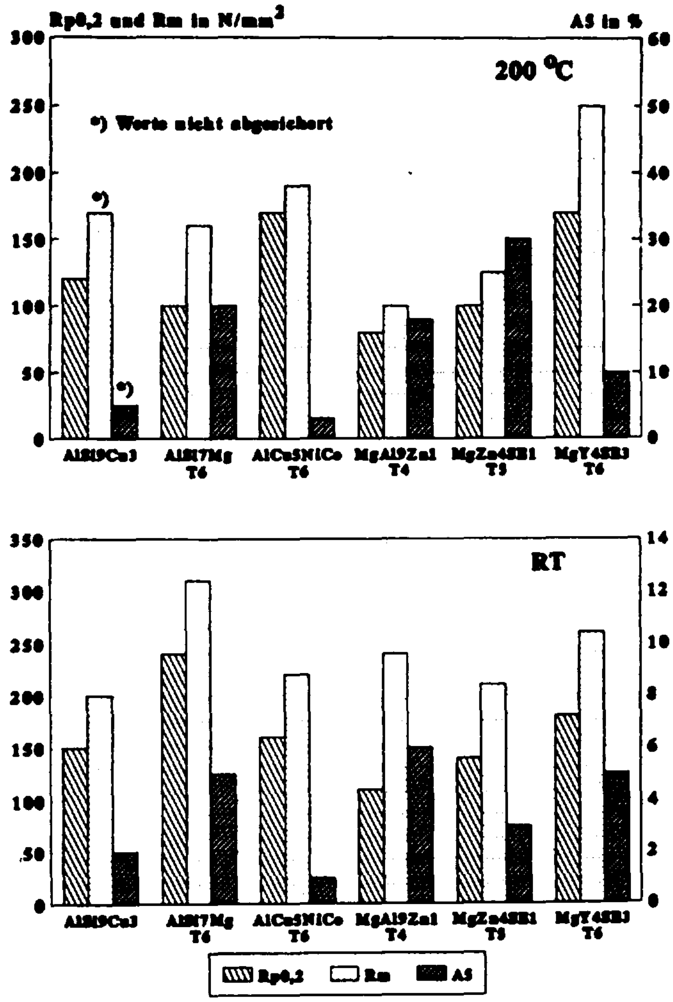


Figure 43: Properties of selected aluminium and magnesium alloys

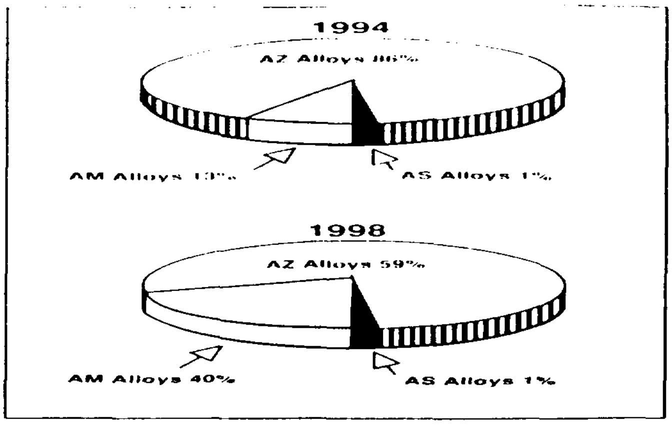


Figure 44: Magnesium alloy utilization trend 1994 - 1998

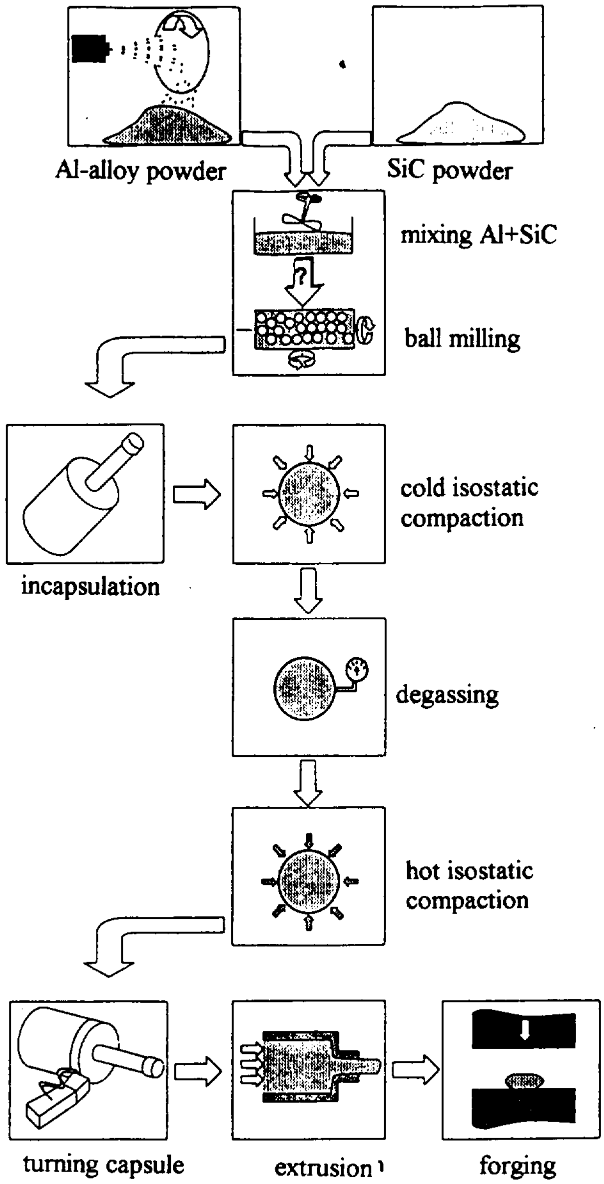


Figure 45: Powder-metallurgical production of particulate reinforced aluminium

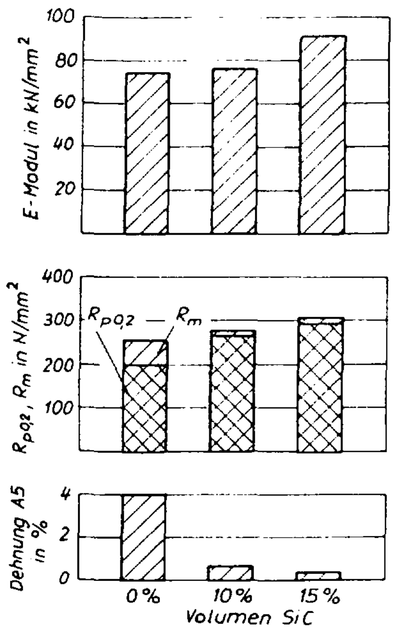


Figure 46: Typical properties of melt metallurgical produced particulate reinforced aluminium

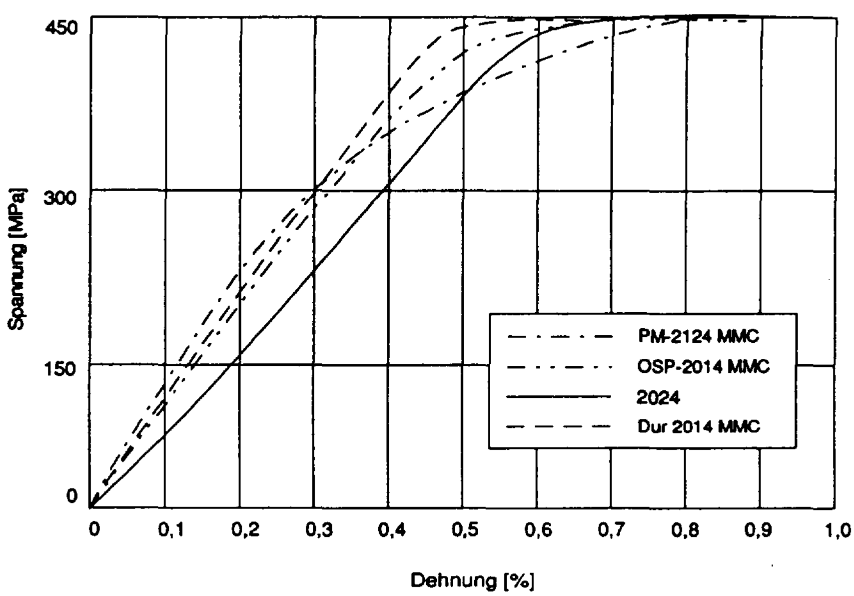


Figure 47: Comparison of the stress-strain behaviour of prticulate reinforced aluminium alloys produced by different technologies. The 2024 alloy is not reinforced. PM means Powder Metallurgical, OSP means Spray Deposition (Osprey), Dur means Duralcan process (melt metallurgical)

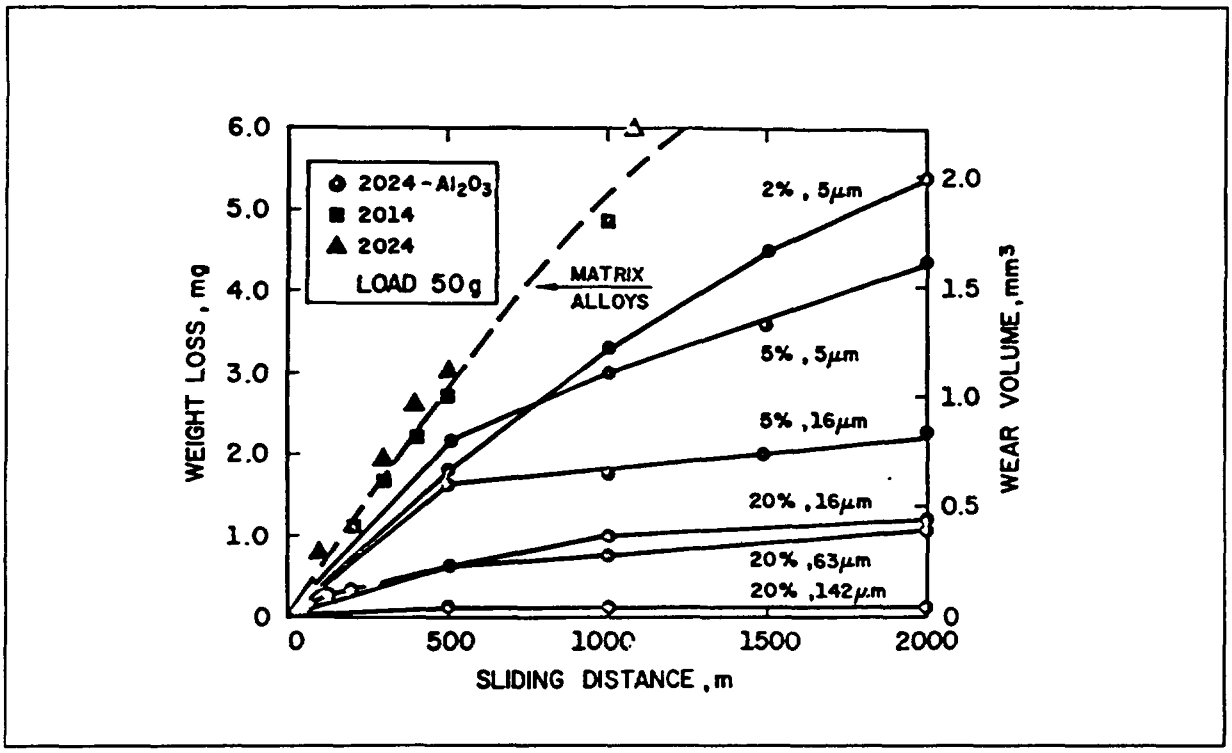


Figure 48: Weight loss vs. sliding distance for different particulate reinforced aluminium alloys

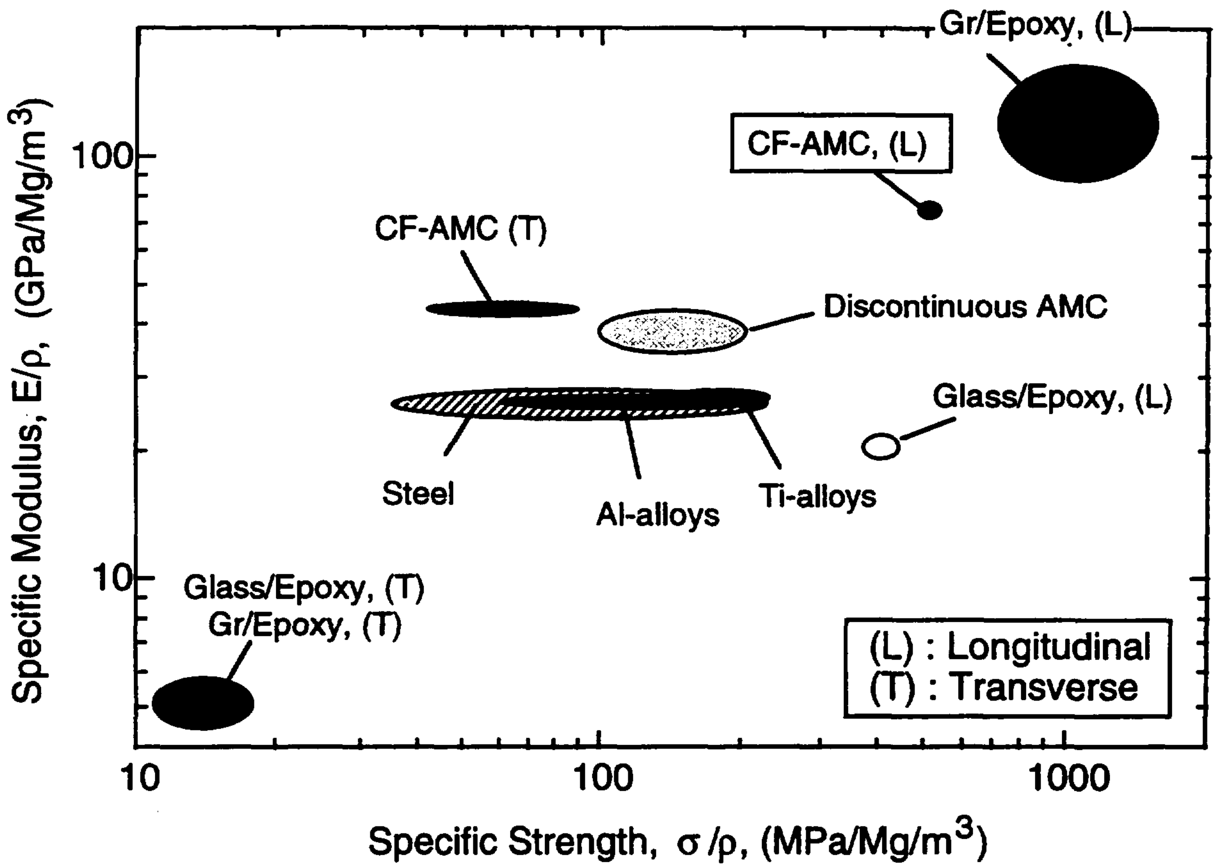


Figure 49: Specific modulus vs. specific strength for selected materials

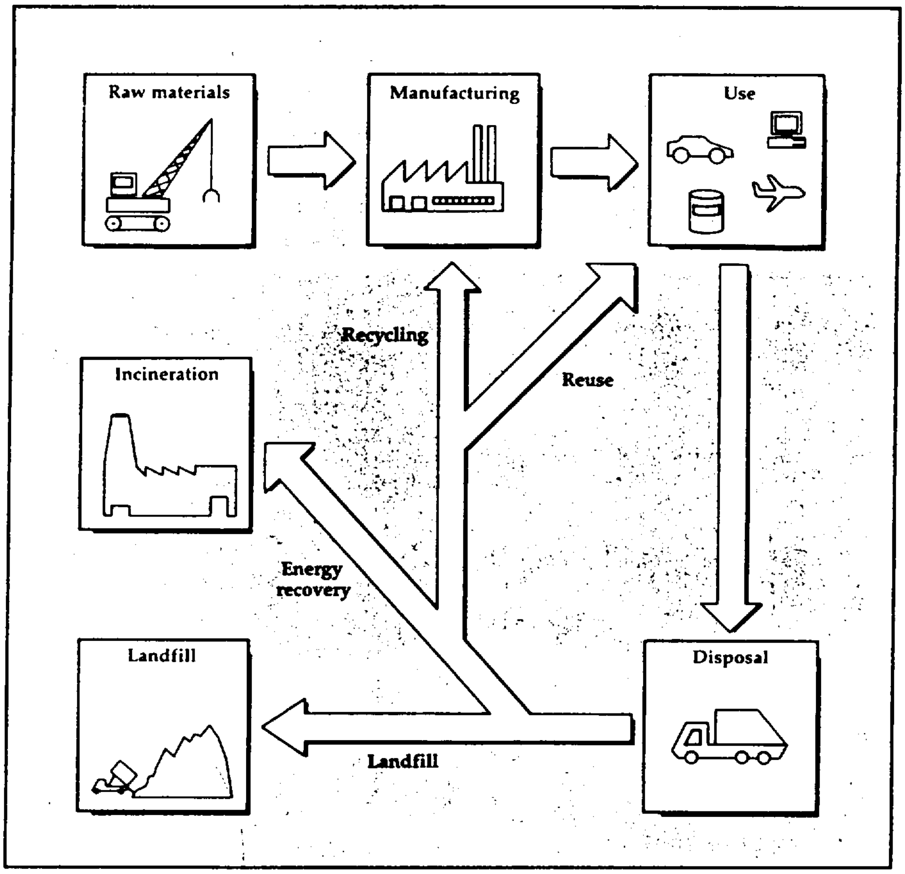


Figure 50: Lifecycle of materials beginning with raw materials

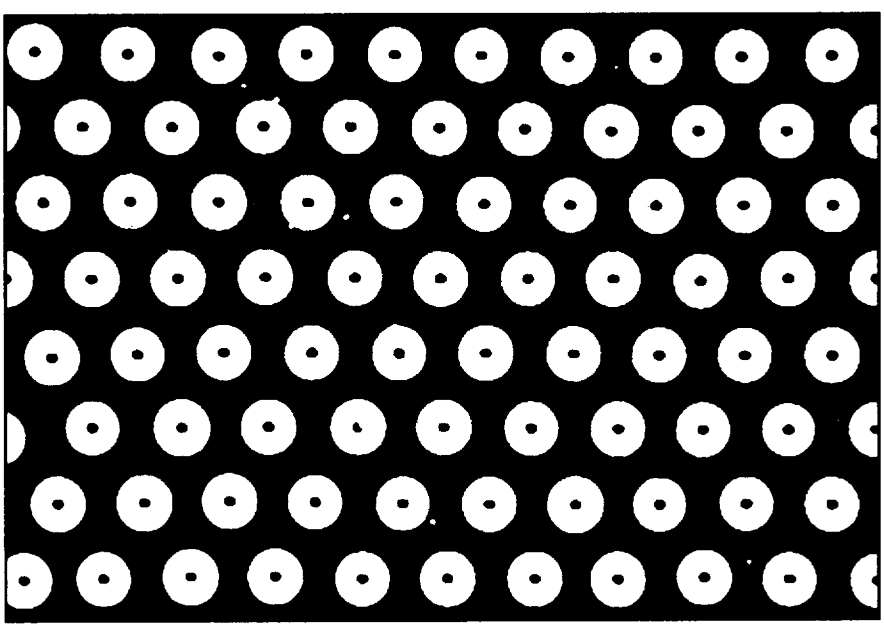


Figure 51: Cross-section of a SiC long-fibre reinforced titanium matrix composite

Abriviations

CTE	Coefficient of thermal expansion
DBTT	Ductile Brittle Transition Temperature
HIP	Hot isostatic pressing
CIP	Cold isostatic pressing
RT	Room temperature
VPS	Vacuum Plasma Spraying
SHS	Self propagating high temperature synthesis
TMT	Thermomechanical treatment
SRP	Smelting reduction process
MA	Micro alloyed
PA	Phosphorus alloyed
YS	Yield strength
UTS	Ultimate tensile strength
CISC	Current Induction Skull Crucible
DS	Direction Solidification
SCS	Single Crystal Solidification
DP	Dual Phase (Steel)