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ADVANCES IN MATERIALS TECHNOLOGY MONITOR

VOLUME 2, NUMBER 3, 1995

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

Vienna, 1995

ADVANCES IN MATERIALS TECHNOLOGY MONITOR

Vol. 2, No. 3, 1995

CONTENTS

UNIDO's *Advances in Materials Monitor* is established as a mechanism of current awareness to monitor developments in the materials sector and to inform governments, industry and academia, primarily in developing countries.
The *Monitor* is issued four times a year and distributed free of charge to readers in developing countries.
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Published in 1995 by the United Nations Industrial Development Organization (UNIDO)
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ISSN 1020-2978

TO OUR READERS

Ozone thinning, the greenhouse effect, global warming, the lack of drinking water - these are the alarming key words 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. The energy consumed for heating, cooling, transportation, industry and the generation of currents increases from year to year due to the progressive tendencies in global industrialization, increasing prosperity, and finally due to the rapid growth of the human race.

Studies show the technical feasibility of switching energy-consuming processes to alternative energy sources, thus avoiding 75% of CO2, but merely doubling the specific energy price. However, international and intercontinental economic competition makes such a step virtually improbable. Thus, only competitive, conventional technical solutions are practical, which promise a stepwise reduction in the emission of harmful reagents.

Taking into account the rapid increase in energy and raw materials consumption, caused by the prosperity of industrialized countries and the increasing industrialization of the developing countries, short-term solutions are necessary. The main demand is a systematic decrease in the consumption of fossil resources and raw materials.

Solutions are fundamentally based on the reduction of weight, improvement of energy efficiency, applications based on natural raw materials, optimization of production processes and recycling of materials. The complexity, as well as the potential of materials-based solutions to reduce the emission of reagents are obvious. Current research in the field of materials engineering clearly shows the path towards tailor-made materials for specific operating conditions, by applying material composites and compounds.

In this issue of the Monitor, 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 and transport. Focusing on the emission of reagents and saving energy and raw materials, solutions from the materials research point of view are highlighted.

Vladimir Kojamovitch
Technical Editor

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SPECIAL ARTICLE

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

I. TECHNICAL SOLUTIONS WITH THE AID OF ADVANCED METALS

Heinz F. Voggenreiter, Rolf Hömann
Germany

1. *Introduction*

Ozone thinning, the greenhouse effect, global warming, the lack of drinking water—these are the alarming key words 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 consumed for heating, cooling, transportation, industry and the generation of currents increases from year to year due to the progressive tendencies in global industrialization, increasing prosperity, and finally due to the rapid growth rate of the human race. Thus, the emission of so-called greenhouse gases and aerosols is further 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 in the surface air temperature of up to 2.5° C by 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 are leading industrialized countries to call for a reduction in energy consumption. In the course of industrialization, the semi-industrialized countries counteract this positive development by increasing their energy requirements, especially those for current generation and industry, by insisting on the use of their own local fossil energy resources. Nevertheless, at present the industrialized countries are the major initiators of air pollution. Figure 1 shows the USA, the former USSR and the People's Republic of China having the highest percentage share in the world-wide emission of greenhouse gases from different countries.[1]

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

Because of the impossibility to reduce the 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 feasibility of switching energy-consuming processes to alternative energy sources, thus avoiding 75 per cent of CO_2, but merely doubling the specific energy price. However, international and intercontinental economic competition makes such a step virtually improbable. Thus, only competitive, conventional technical solutions are practical, which promise a stepwise reduction in the emission of harmful reagents.

2. *Fundamentals*

Future-oriented solutions to satisfy the demand of mankind for energy are mainly based on the search for alternative energy resources. A lot of investigations are being conducted on energy production using 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 greatly reduces 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 a systematic decrease in the consumption of fossil resources and raw materials.

Solutions are fundamentally based on the following technical approaches, mainly driven by the demand for fuel and raw materials saving (figure 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, lightweight designs, in addition to the use of advanced materials such as modified plastics, metal alloys and natural materials such as cotton, coco fibre and natural rubber. The light-weight effect is mainly based on the following materials properties:

- Specific weight;
- Young's modulus (stiffness);
- Strength.

A lower material specific weight will directly reduce the application weight. However, materials with a low specific weight but insufficient stiffness and strength only moderately contribute to a reduction in 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 by 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 whereby 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 high 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 higher temperatures. As a consequence, the reduction of stress by enlarging the part's dimensions results in an increase in weight. This fact shows the necessity to develop new plastics and alloys, as well as modifying 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, 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 the optimum formability of the above-mentioned lightweight materials in order to make maximum use of their weight-reduction potential.

Both material and process costs 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 jointed machine parts. Thus, the total efficiency can be improved by:

- Optimizing the thermodynamic process of the thermal engine;
- Increasing the admissible rate of revolutions by reducing the weight of oscillating engine parts;
- Reducing friction between the 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 achievable.

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 high 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 operational environment (corrosive, inert medium, etc.), an additional acceptable resistance of the material to high-temperature corrosion and oxidation is required. Concerning the mechanical properties, optimization of the material's chemical composition and solutions based on material composites is being pursued. Corrosion, respectively oxidation behaviour, is improved by the defined adaptation of the chemical composition, or by applying protective coatings. However, in most cases the first intrinsic solution exhibits contrary effects on the mechanical properties and oxidation corrosion resistance.

The demand for increased revolution rates for oscillating or rotating engine components leads to the necessity of materials to have a 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 light-weight structures. However, the combination of a low specific weight and high mechanical and thermal loads demands 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 these new requirements. Process steps like ore-drying, coke production, etc. must be critically discussed. 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-strengthened 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 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 to a deterioration in the quality of the materials. Additionally, research activities over the past few years have been based more and more on adapting materials' properties to 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 these different materials for recycling is a severe problem. This shows that the production of tailor-made materials often counteracts the recycling requirements.

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

To summarize the above-mentioned aspects, the complexity, as well as the potential of material-based solutions to reduce the emission of reagents are obvious. Current research in the field of materials engineering clearly shows the path towards tailor-made materials for specific operating conditions, by 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 recyclable material. Thus, the development of new advanced materials will always feature the conflict between the 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 crticial technologies, such as heating cooling, current generation, industry and transport. Focusing on the emission of reagents and saving energy and raw materials, solutions from the materials research point of view, are highlighted.

With respect to the above paragraphs and the wide fields of research 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:	Polymers
Part IV:	Natural materials
Part V:	Production processes
Part VI:	Recycling
Part VII:	Global view on life cycle pollution

In the following study, the tendencies concerning metal-based solutions for light-weight structures and the increased efficiency of thermal engines are shown. The resultant development of new, or modified, metal alloys is described and discussed. These results provide the necessary baseline for further 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 energy consumed and harmful reagents emitted 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 the benefit of new materials solutions for the reduction of environmental pollution be defined within statistical limits.

4. *Tendencies in technical solutions for 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 keep the level of fuel consumption constant, because of weight-intensive security devices such as airbags, ABS etc. In trains, the requirements for comfort (air-conditioning, kitchen) are weight-intensive but necessary components of modern train systems. Trucks 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. It is often 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 therefore new light-weight constructions will be established only when there is a significant marketing advantage. This advantage could be an improved environmentally friendly product. In the European automotive industry an additional expense of USS 6-8 kg weight reductions is accepted due to the fact that 100 kg weight reduction effects a 0.3-0.6 litre 100 km 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 allow a saving of about 20 kg in a car body of 400 kg raw weight. The weight reduction increases with the amount of light metals used. A pure aluminium car (same raw body weight) will be about 130 kg lighter than a conventional steel body but nearly 40 per cent more expensive (see figure 3).[3] 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 transportation 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 friendly 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 industry to develop products featuring a low energy consumption. Some politicians in Germany demand a fuel price of US$ 3.30/litre (exchange rate $1 = DM 1.50) in the year 2005. Today we have a price of US$ 1/litre. If only half this demand is followed, we will have a fundamentally new situation in European industry.

Today there are developments under way in all parts of the transportation system industry to produce 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 figure 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 present time the interest in magnesium is increasing, although in the past a lot of magnesium was used, especially in automotive systems. Because of this fact, the emphasis of this part of the study focuses on basic magnesium technology and the major differences between magnesium and aluminium in terms of their 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 then was the remaining stock of magnesium from war aeroplane production. At the end of "Beetle" production in 1980, the amount of magnesium used was about 345,000 t.[6] Magnesium offers a whole number of advantages for the automotive industry:

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

Magnesium with a specific weight of $\rho = 1.7$ 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 figure 5a.[6] It is obvious that magnesium offers competitive properties in comparison with other materials.

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

- Nearly the same stiffness/weight ratio as; and
- Higher strength/weight ratio,

than aluminium and steel.

The major problems in the use of magnesium are its about twice higher price as 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 therefore to be considered in every construction containing magnesium. Furthermore, exposing magnesium to higher temperatures, in the range of 120° C and higher causes 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 achieved in this special application is from 4 kg (steel component) to 1 kg (magnesium component). The part is, like nearly all magnesium parts, die-cast. Alloy AM60 is also used for instrument panels and steering wheel columns. 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 per cent rare earth metals and has a high creep resistance. Its operating temperature of 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 automotive makers are die-castings. Some applications in die-cast magnesium are shown in figure 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 a thinner wall thickness than aluminium) is not often possible. In the past few years, aluminium often won the cost competition. Aluminium has many advantages for structural applications. Its easy availability, in combination with low and relatively stable prices, makes aluminium a very interesting engineering material. Aluminium offers high stiffness, low weight ($\rho = 2.7$ 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 the magnitude of magnesium, but it has a lower tendency to galvanic corrosion. The main problem with magnesium is often its poor creep resistance. At higher 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 a low strength and ductility.[7] Sometimes the combination of cast and wrought alloys in the same product is of great advantage and then the demands of mechanical engineering 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 the knots and the rest of the structure apart makes the recycling process expensive.

4.1.2 Aerospace applications

General overview

For aircraft, light-weight construction is a fundamental assumption in order to guarantee the function and the economic efficiency of an aeroplane. Every kilogram of weight reduction increases the payload and decreases fuel consumption. In contrast to the situation in the automotive market, the accepted cost increase per kilogram weight reduction for aeroplane applications is about US$ 600-800.[10] Further, the production period of such 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 period.

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 transportation 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 be reduced by 10 per cent, the density must also be reduced by 10 per cent. In this case, the strength has to be increased by 35 per cent, the stiffness by 50 per cent and the fatigue tolerance by 100 per cent. 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 the 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 (figure 7). In the next paragraph of the study, a general overview of the most important development approaches, and a short description of the "state of the art" will be provided.

In the past few years the content of light metals, especially of aluminium, has decreased in aeroplanes. The reason is simple: the development of advanced plastics. Figure 8[12] shows an increase of the content of plastic-composite materials and the decrease of aluminium from more than 70 per cent (A300) to about 65 per cent 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 per cent. 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 a reduced specific weight, due to the use of lithium. It features a 200 per cent higher fatigue-crack-growth resistance than AA7075-T651 (AlZn-based and heat treated). It is also reported to have a 35 per cent 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 per cent could be realized for the above-mentioned parts (as related to conventional aluminium alloy). The cost per kilogram weight reduction is US$ 480[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 fulfil 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 a high purity so as to secure a 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 the past few years a new alloy—AA6013 (AlMgSiCu)—has been developed and is under practical examination. Its major benefit is good welding abilities and a 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 the 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. Whiskers in addition are said to cause cancer, and the benefit of the properties of the composite is relatively low compared to other reinforcement materials.

The main effect of 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 strain-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 effects. The damage tolerance will also decrease. Because of the latter reasons, the usage of MMCs in aerospace applications, as well as in automotive applications, has not yet reached the status of mass 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 figure 9).[15] 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 figure 10).[16]

Summarizing the above-mentioned 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 (especially for the wings);
- Good weldability;
- Easy reproduction of the material 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 a low specific weight, but high strength and stiffness, allow the reduction of oscillating masses. This results in a higher number of revolutions and therefore 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 purpose 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 for 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 thermomechanical 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. Therefore 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 mass production of trucks is the local reinforcement of the critical points by aluminium matrix composites (MMC)[17] or, as is under investigation, by titanium aluminides (figure 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 per cent (Al-base alloy) to 30 per cent (Mg-base alloy) lower mass.

A further potential for fuel saving appears in the reduction of friction in the valve mechanism. Energy loss due to friction is mainly caused by the valve tappet sliding on the cam of the cam shaft.[2] It is evident that high valve spring forces increase the 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 (figures 12 and 20), the spring force and thus friction can be drastically reduced by decreasing the mass moved. A reduction in fuel consumption of up to 4 per cent in the ECE cycle is achievable (figure 13). Figure 14 shows the light-weight potential of titanium alloys and ceramics as 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 its superior oxidation resistance. Whether ceramics, titanium or aluminides are used for valves in automotive engines in the 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 per cent to the moved masses in the valve system. With the use of a cold-formable and age-hardenable beta titanium alloy Ti13V11Cr3Al, the mass can be drastically reduced by 130 per cent, as 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 per cent.[2]

The development and application of high-temperature metal alloys is limited to a few motor components, such as catalysts, or the combustion areas of high-performance diesel engines. Direct fuel injection systems that 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 of up to 1,300° 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 process cycle 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 1,400° 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 KMW 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 (figure 16). In the following sections, only the main demands for these critical engine components are briefly outlined.

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 which is only achievable by casting technology. Due to the 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 the intrinsic material resistance and protective coatings. Thus, for new materials to withstand higher temperatures, thermal fatigue resistance and creep strength have to be improved. Standard alloys used in the past 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). In addition 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 single-crystal casting have led to an overall improvement in mechanical properties. With these techniques, the 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 per cent to 85 per cent of the solidus temperature lead to fast changes in the microstructure, and thus to a decrease in the 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 the mechanical properties in general counteracts the oxidation and high-temperature corrosion behaviour.

Thus, for higher operating temperatures, new metal composites are being 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 high temperatures.[23]

As the specific weight of nickel and cobalt base alloys is high, new intermetallic high-temperature, light-weight alloys with the appropriate mechanical properties and intrinsic good oxidation behaviour are under investigation. Titanium alloys were developed showing a good microstructural stability of up to 650° C (IMI834). Application at this temperature level was rejected due to the detrimental oxidation and corrosion behaviour. Promising candidates are aluminides of titanium (TiAl, Ti_3Al, and alloys) and nickel (NiAl, Ni_3Al, and alloys), due to their temperature potential, and up to 50 per cent 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. Figure 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 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 the impurities caused by the 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 have forced the steel industry to flexibly adapt their product qualities to the demands of the customer. 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 a new flexibility in producing custom-made and application-tailored components.[25] 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 a simplification of the process, therefore helping to avoid, or reduce, polluting emittant output. New computer technologies have permitted 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 a 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 a high yield strength, steels are excellent candidates for light-weight structures. Improved strength, cold drawability and high energy absorption in crash situations for automotive bodywork sheets, which are the basis for steel-based, light-weight structures, are achieved by manipulating the microstructure with the aid of advanced materials treatments. Additionally, new alloys are under development in order to meet 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 steelmakers and the manufacturing industry. Nevertheless, a weight-saving potential of about 25 per cent and more compared to today's weight of a car could be attained by substituting 50 per cent 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 litres 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 346.10^6 litres per year in western Europe.[29]

Developing high-strength steels with good cold drawability began in the 1970s. 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-galvanized 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 figure 18.[29]

Figure 19 shows the increasing demand for high-strength steel strips by the automotive industry over the past 10 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 per cent 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 increase 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 the stiffness and the yield strength of the steel. In addition 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 so conditioned that hardening occurs at temperatures above 120° C, due to controlled carbon ageing. 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 a minimum C content, BH steels are decarburized by vacuum annealing. The chemical composition of a typical representative of the BH steels (ZStE180BH) is given in table 6.

The drawability of typical bake-hardening steels is comparable to the deep-drawing steel St14, as is shown in figure 21.[29] Compared to phosphorus-alloy 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.[29] Figure 22 documents an increase of the BH effect with both increasing temperature and time for the non-deformed state and the 2 per cent-deformed state. An improved crash behaviour of BH steel ZStE180BH, compared to the 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 an increasing strain rate.[31]

Bake-hardening steels have now reached a stage 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 in production energy.

5.1.3 Tailored blanks

Tailored blanks were introduced on to the automotive market by Thyssen Inc. Germany in the late 1980s. A tailored blank is the combination of steel sheets of different quality, surface coating and thickness by laser beam welding (figure 23). This procedure offers the possibility of combining 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 steel types can be used in crush sections, while sheet sections with higher strength and thickness are used in load-bearing sections of the structure. Figure 24 shows 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 lifetime in addition to a decrease in weigh .

A supplementary benefit of the use of tailored blanks, in addition to the great weight reduction potential, is the reduction of finishing steps, a 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 vanes. Their potential is enhanced by the ability to harden by precipitating the $\gamma'(Ni_3Al)$-phase, in addition to a good oxidation resistance. However, coatings are necessary when using these alloys at temperatures above 1,000° C in an oxidizing atmosphere. As will be described in subsequent chapters, oxide-dispersion-strengthened (ODS) Ni-based variants offer a higher strength and fatigue resistance. The drawback of ODS-Ni alloys is a 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 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 impoverishment 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.[22] Thus, new melting technologies are under investigation with the aim of trying to avoid the 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 (figure 25). Thus, a high degree of purity can be achieved.

In addition 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 an 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 (figure 26).[23] For SCS, the probability of more than one grain forming is reduced.

The development of new Ni-base alloys tends to reduce the chromium content in order to attain the maximum solubility of $\gamma'(Ni_3Al)$-forming elements. An increase in the γ'-precipitation, in addition to directional solidification, allows an improvement in both thermal fatigue and creep resistance. Alloys of the third generation owe their improved creep behaviour to the addition of refractory elements such as 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. Figure 27 shows the possible increase in temperature capability with a decreasing Cr content. The values are related to conventional cast alloy 738 (CC). A rise in the operating temperature of about 110° C seems to be possible by using Cr-poor alloys in addition to the SC process.[11] However, the poor chromium content requires coatings that protect it 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.[12]

Titanium aluminides are 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. Figure 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 producing a fine equiaxed grain and a flaw-free structure.[20] Appropriate processes to achieve a fine grain are isothermal forging, extrusion or powder processing.[22] The resulting excellent specific yield strength (strength/weight) as compared to Ni-base alloys and near-α titanium alloys of up to 700° C is shown in figure 29.[10] However, the specific yield strength is lower than that of the Ti_3Al-based alloy. The fatigue strength of defect-free material is very high at 80 per cent to 90 per cent of the yield strength. Micro-pores and notches significantly reduce the life span. Application of TiAl alloys is possible up to 750° C and thus offers an around 100° C temperature potential higher than Ti_3Al.[24] At higher temperatures, resistance to creep and oxidation is insufficient for its 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 per cent of oxygen.

$Ti_3Al(\alpha_2)$-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 the Super-alpha-2 alloy, Ti62Al26Nb 10Mo1. Unfortunately, this alloy lacks acceptable formability and is susceptible to hydrogen embrittlement.[15] 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 (figure 29). The processes to enhance room temperature fracture toughness by grain refining are similar to those of TiAl alloys. The 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 through alloying with Si up to 8.5 per cent leads to the formation of an eutectic alloy system T_3Al-Ti_5Si_3, with improved mechanical properties and oxidation behaviour.[16] A comparison of the oxidation behaviour of Ti_3Al alloys with TiAl and other Ti alloys is given in figure 30.[17]

Due to the above-mentioned inherent material problems, Ti_xAl-based alloys are still under development and not yet applied commercially. A further problem is the very limited reproduction abilities of materials properties from different suppliers and different batches.[illegible] 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 per cent to 80 per cent and a specific strength 50 per cent to 75 per cent greater than Inconel Alloy 718 at 700° C is reported.[illegible] TiAl alloyed with 0.3 per cent Sb and 0.5 per cent Hf exhibits a 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 a sufficient creep strength of both types of alloys TiAl and Ti_3Al at temperatures above 600° C makes researchers 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, besides a low room temperature ductility, feature insufficient strength and creep resistance at high temperatures.[illegible] 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 per cent compared to Ni-base superalloys.

Ni_3Al

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

NiAl

NiAl exhibits an excellent oxidation and corrosion behaviour under temperatures up to 1,300° C. Additional advantages as compared to Ni-base superalloys are a four-times higher thermal conductivity, a lower coefficient of thermal expansion (CTE), and a reduced specific weight. A further benefit is a better resistance to thermomechanical fatigue. However, high-temperature strength of about 40 N/mm^2 at 1,000° C, creep strength at high 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 is only 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.[illegible] 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 an increase of 0.2 per cent proof stress with a rise in the Cr content and its temperature behaviour.[illegible] Unfortunately, the increasing u. content of Cr counteracts oxidation resistance.[illegible] Processing the alloy greatly influences its strength and fracture toughness due to microstructural effects such as grain size, second phase distribution, etc. Figure 32 shows the difference in elongation and fracture toughness, depending on the processing used (HIP resp. HIP and extrusion).

The above-mentioned facts give a distinct picture of the situation, namely that the main problems of Ni aluminides needing 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.[illegible] Investigations on NiAl - 5%Cr and NiAl - 5%Nb particles show that there is a toughening effect, but it is metastable. After exposure to temperatures higher than 1,000° C, Nb and Cr particles become as brittle as the NiAl matrix, due to solid-solution reactions.[illegible] This means a limit to the operating temperature well below 1,000° 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 density 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 temperatures 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 towards 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 (MMCs), a composite of Mg_2Si, with either an Al matrix or an Mg matrix, was produced and investigated.[illegible]

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 as compared to the die-cast standard piston alloy AlSi12Cu MgNi. 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 when compared to the standard AlSi piston alloy, but consequently higher than that of alloy MgY5.2RE3Zr0.7 (WE54). Figure 33 shows a lower drop in Young's modulus with an increasing temperature compared to the standard piston alloy.[illegible] The behaviour of the yield strength of Mg-Mg_2Si is documented in figure 33. In the temperature range of about RT to 270° C, the Mg-Mg_2Si alloy shows a significantly lower yield strength as compared to the standard piston alloy and alloy WE54.[illegible] 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.[illegible] The CTE is reduced with an increasing volume fraction of Mg-Mg_2Si, as shown in figure 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-respectively 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 per cent with Al-30%Mg_2Si and 30 per cent with Mg-20%Mg_2Si. Additional benefits are the lower CTE and the good processing capabilities. However, these types of alloys have been under investigation 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 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).[45] All these process routes aim to produce near-net-shape parts.

$MoSi_2$ offers excellent corrosion and oxidation behaviour in oxidizing atmospheres at temperatures up to 1,600° C, due to the formation of a dense SiO_2 surface layer. Under a continuous thermomechanical load, a maximum operating temperature of about 1,200° C is achievable.[45] Due to the covalent-metallic bond, $MoSi_2$ exhibits high thermal conductivity (24.1 W/mK at 1,200° C), and a 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, the oxidation stability is based to a very great extent on the 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 little data are available. But investigations on second-phase strengthened alloys such as $MoSi_2$-WSi_2, respectively $MoSi_2$-SiC are under way.[46]

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 per cent of the alloy's melting point, compared to 40 per cent for strain-hardened alloys and 60 per cent for precipitation-hardened alloys. Recent investigations 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.[26] 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 attrition 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 generally 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 3vol%. 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 (figure 35).[47] Creep tests show that when subjected to a load of 160 MPa, a strain threshold of about 0.3 per cent is reached, at a proof temperature of 275° C (figure 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 (figure 37).[5] Figure 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.[5] 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, contrary to the Ni-base ODS alloys exhibiting operating temperatures of about 90 per cent of their melting point T_M, ODS-Al alloys just reach temperatures of about 50 per cent T_M.[26] The interest in new "high-temperature" Al alloys for structural applications calls for further investigations 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 thermomechanical 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 high 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. Figure 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 1,100° C-1,150° 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 Ni-Al-based matrices by solid solution hardening, or precipitation hardening mechanisms, failed for low strain rates and high temperatures,[illegible] new approaches are being pursued concerning oxide dispersion strengthening. ODS-NiAl and NiFeAl alloys are reported to be produced by mechanical alloying with 1 per cent to 2 per cent 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.[illegible] 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 developments 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 chromium content, possess excellent oxidation behaviour. Thus, ferritic ODS Fe-base alloys like MA 956 and PM 2000 were developed, consisting of Fe20Cr4.5A10.6Ti (MA 956), respectively Fe20Cr6A10.6Ti (PM 2000) and 0.5 per cent 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 1,250° C, by forming adherent, stable Al_2O_3 oxide films.[illegible] However, the creep strength of MA 956 amounts to about 60 per cent of the values attained with Ni-ODS alloy MA 754, at temperatures between 1,000° C and 1,100° C, but extends up to 1,350° C.[illegible] The maximum operating time in a combustion gas atmosphere for MA 754 is about 7,500 hours at 1,250° C.[illegible] PM 2000 shows a better oxidation resistance, due to the higher Al content and very good creep behaviour at temperatures up to 1,250° C. For both types of Fe-ODS alloys, production and the resulting microstructure significantly influences the final high-temperature properties. Figure 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 1,250° C. Note that Ni-ODS alloys must be coated for operating temperatures from 1,000° C to 1,100° 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 reported on the production of a particle-dispersed steel with the highest Young's modulus ever reached for steel, of about 265 to 285 GPa.[illegible] This Fe,13-16Cr,1-5Al,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 1,200° C to 1,400° 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 optimization and modification of known alloys, and the development of new process technologies to increase productivity and 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 thixomoulding, are approaching large-scale production. The die-casting process today allows almost pore-free manufacturing of castings in an extremely short time-span.

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 a high purity and processing is easier. So wrought alloys are only used when they are really needed.

Aluminium-lithium alloys

Aluminium-lithium alloys offer advantages such as low density and high modulus. Lithium is the lowest-density metallic element ($\rho = 0.534$ 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 per cent leads to a weight reduction of about 10 per cent.[illegible] 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 the 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.[illegible]

New technologies such as vacuum refining are under development so as to obtain high-purity alloys with high lithium contents of up to 3.3 per cent. It seems that aluminium-lithium alloys are very sensitive to impurities, especially hydrogen and alkali metals. Figure 41[illegible] 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

High-strength aluminium alloys are undergoing continuous development. The alloys of the 7xxx series are especially 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 applications.

In the development of high-strength aluminium alloys, the powder metallurgical route offers one of the most interesting ways to obtain an even higher strength, in combination with increased fracture toughness, than available 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 advantages 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.[58]

The powder metallurgy processes have the disadvantage of their high cost. On the other hand, some lightweight 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 no PM processes are of any use for large parts, like whole engine blocks.

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

- 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 continuously. In figure 42,[60] the North American magnesium die cast alloy consumption is shown. If this course is followed in the coming years, the importance of magnesium will greatly increase.

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]

Figure 43[61] shows the mechanical properties of some selected magnesium alloys as 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 figure 44).[7]

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 fulfil 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 the 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 electricity.

Magnesium offers many economic and ecological advantages when the producing area has the following available:[62]

- Electricity generated through water, solar, or wind energy;
- Seawater.

5.5.3 Reinforced light-weight alloys

Metal matrix composites (MMCs) have a 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 high temperatures.[63] The three most important light-weight alloy systems, aluminium, magnesium and titanium, are suitable for reinforcement. An overview of these three groups is given in table 10.

The most interesting MMCs are those that consist of fibres, or particles, in a common matrix material. They have significant advantages over monolithic metals and polymer matrix composites (PMCs). 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 MMCs, when not extruded, are isotropic.

The main parameters influencing a particular-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 MMCs are based on an aluminium matrix, although many of the process technologies can be transferred to magnesium.

The main disadvantage of MMCs is the complex solidification process in production and machining. A strong connection is essential between the particle and the matrix. This interface should be in a thermodynamical balance to obtain a stable microstructure at high temperatures. The major production processes for particulate MMCs are as follows:[illegible]

In powder metallurgical processes, a preconsolidated 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.

Through 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 2-4 hours are necessary, normally the particles have dimensions of 1-3μm. The optimum size of the matrix powder is about twice that of the reinforcement. Coarse matrix powders (>50μm) lead to the formation of large particle-free zones in the composite,[illegible] and therefore to inhomogeneous material properties.

The next step in the solidification process is pressing. Due to poor thermal conductivity, the powders have to be cold pressed first. 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.[illegible] At the moment they deliver the best available metal matrix composite products. A description of the process technology is given in figure 45.[illegible]

Infiltration processes are used to produce particulate- or fibre-reinforced MMCs by infiltration of preforms with liquid metal. Usually, minimum reinforcement volume contents of 45 per cent 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 the formation of intermetallic phases or oxides is a great problem in this technology, as well as the chemical reactions between the fibre and the melt. The infiltration time is usually about one second per mm² infiltration cross section.[illegible] 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 necessary to obtain a pore-free material. Another approach in infiltration technology 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 metal-metallurgical and powder metallurgical products. The molten particles are solidified on a cooled substrate, cooling rates of about 10^{3}-10^{6}K/s can be reached; in comparison PM offers a cooling rate of about 10^{4}K/s. In the as-sprayed condition, the density of the material is about 95-98 per cent, therefore the pre-solidified material has to be extruded before use because of its porosity and low ductility.[illegible]

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

The major economical problem in the Osprey process is the so-called overspray. Usually 30-50 per cent 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 an aluminium (AA 6061) melt. The *in situ* process technology is very sensitive to impurities in the basic alloy and the process parameters. In the future, the importance of *in situ* MMCs may increase because of their specific properties. They offer:

- Small particle sizes (< 3μm; common particle sizes in other MMCs 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 ease of clarification, the smaller the particles, the better the fatigue behaviour of the composite. "Big" brittle particles, as in the most common particulate-reinforced aluminium alloys, lead to a low ductility and fracture strength. Research and development in these areas are being increasingly pursued. If these materials can maintain what they promise, a large market will appear for these materials over the next few years.

The melt metallurgical process is the cheapest solidification process for aluminium-based MMCs. 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 vacuum by mechanically stirring the melt. The stirring process is usually carried out for a time of up to 70 minutes. The MMCs so obtained can be cast in conventional moulds, and they are therefore cheap. Currently, the price of 1 kg is about twice that of a conventional AlSi cast alloy. Typical properties of cast MMC, in comparison to the unreinforced matrix, are shown in figure 46.[illegible] 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 a 50 vol.% alumina fibre (diameter 100 μm) reinforced AlZn alloy, produced by an investment casting infiltration process, a Young's modulus of more than 130 GPa and a maximum bending stress up to 900 MPa was measured.

Reinforcement by the use of particles causes an isotropic change in the properties, although the strength does not increase significantly. Sometimes the yield strength increases a little, depending on the production process. The increase of elastic modulus at a constant tensile strength can be seen in figure 47. It can be seen that the yield strength is, in the case of PM material, lower than in a conventional wrought alloy. Typical properties of some advanced PM-aluminium MMCs are given in table 12. The most important property of these alloys is 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 aluminium has a CTE of 23×10^{-6}, the reinforced alloys offer a CTE in the order of magnitude of $16\text{-}18 \times 10^{-6}$.

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 (four 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. Figure 48 shows the improvement in wear resistance caused by ceramic particles.

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

Reinforced titanium

Titanium is usually reinforced with SiC in a continuous fibre form. The fibres are coated by electron-beam deposition with high-purity Ti-6Al-4V in a controlled atmosphere. The cross-section of a typical Ti6Al4V SiC[illegible] composite is shown in figure 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 a 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 US$1,000 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 reinforcement of magnesium by the use of particles or fibres is one of the most interesting parts in future material development.

The disadvantages of magnesium such as

- low creep resistance,
- low stiffness, and
- low wear resistance,

can be increased significantly through reinforcement.

This group of materials will be the beginning of a lower structural weight and will 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 the UK 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 per cent, typical particle size is about 10-15µm.

6. *Summary*

6.1 Materials for light-weight structures

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.

Favourite Al alloys are the AlLi alloys with a reduced specific weight and as increased specific stiffness due to Li, or the aluminium magnesium scandium alloys, which 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 a good die-castability will be one of the most important fields in the development of new Mg alloys. Although today the usage of magnesium for parts working at high temperatures in the range of up to 150° C, for example in gear housings, is not possible due to the poor creep resistance of the material, in future these application fields will be of increasing interest for the automotive industry. New alloys containing rare earth metals provide good creep resistance, combined with a high damping performance.

The use of reinforced light-weight alloys will increase at the same rate as cheap process technologies (like the Duralcan process) are available. The tailorable properties of the material offers an on-the-problem-oriented design, and therefore a high weight stiffness or weight strength ratio. 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 uses for magnesium will increase and therefore new application fields can be reached.

It should not 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 life-cycle economics of finished systems, as shown in figure 50. 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 an aluminium aircraft is less than that of a steel aircraft. For the same reason, most car bodies are currently made of steel sheet rather than aluminium. In automotive applications, life-cycle economics are very different from those in airplanes; however the same principles of material selection apply.

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 forces steel producers to develop new steels and processes for steel-based light-weight structures. Due to its high strength, excellent crash behaviour, the low energy requirements 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 the steel-processing industries give a new perspective for the "old" metal steel. The new processes also allow a much easier development of new alloys, and thus accelerate steel research. New computer-aided designing, including computer simulation, allows engineers to make maximum use of the steel properties. These tendencies and the use of tailored blanks and steel types with a higher strength offer an excellent base for new light-weight structures in the ground transportation industry. Comparison of steel-based solutions for light-weight structures with the development of Al-based solutions (e.g. the Audi spaceframe) show that steel is a strong competitor.

The advantage of the steels is the nearly 100 per cent recycling in Europe and North America. This means a primary energy and raw materials saving production. Calculating the whole energy balance of the production process, the use of secondary Al-alloys must be increased from an actual 35 per cent (Germany) to 70 per cent in order to compete with the steel solution in environmental compatibility and cost.[23-24]

6.2 Materials for increased efficiency of thermal engines

Ni-base alloys are commonly the workhorses of high temperature materials. However, the demand for higher temperatures above 1,000° C involves problems like oxidation, transformation of the microstructure and the 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 1,150° C. However, these temperatures necessitate coatings in order to avoid oxidation and hot gas corrosion. A drawback of this ODS alloy is the reduced possible complexity of the component design. For turbine blades, the excellent creep properties are counteracted by a 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-based alloys involves investigations on aluminides for high-temperature applications. The 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_3Al and Ni_3Al are superior to that of the Ni-based alloys and the titanium alloys at temperatures from 700° C (Ti-aluminides) up to 1,000° C (Ni-aluminides). However, drawbacks such as the inherent room temperature brittleness, the difficult formability, the very limited reproduction ability of mechanical properties (Ti_3Al), and the lack of a sufficient creep resistance, delay their use in high-temperature applications. A lot of investigations are being done to solve the problem of brittleness by the addition of alloying elements, or second phase ductilization. Recent investigations on $Ti_3(AlNb)$ show very promising results concerning its formability and room temperature properties. However, in some cases alloying for improved mechanical properties counteracts the oxidation resistance. To improve the creep behaviour, the process of oxide dispersion strengthening is applied to aluminides, especially to Ni-aluminides. The fine dispersed, thermodynamically stable oxides should thus avoid grain boundary migration. However, mechanical alloying, and the subsequent powder metallurgy route, is complex and expensive. Up to now, none of the described aluminides has been transferred 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 silicum (silicides) offer the advantage of a huge 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 1,200° C, with sufficient strength and excellent oxidation resistance, due to silica layer formation. However, room temperature brittleness, severe oxidation in the temperature range of 600° C (pesting) and the difficult processing of bulk materials necessitates 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 per cent, compared to the standard piston alloys. This means an improved efficiency of the engine and thus reduced reagent and particle emission. Additional benefits are the higher stiffness, contributing to weight saving, reduced CTE, higher thermal conductivity and efficient production by the casting route. Because of their properties and their cost-efficient production, they have good chances to be used in mass production.

Besides the oxidation behaviour and the thermodynamical stability of the microstructure, creep resistance is the most dominating factor for high-temperature materials. Creep occurs at 150° C for Al- and Mg-alloys, as well as at temperatures above 1,000° C for Ni-base and Fe-base alloys. Oxide dispersion strengthening by inherent, thermodynamically stable oxides reduces creep. Some ODS-Al alloys show excellent creep behaviour and strength at temperatures up to 300° C. However, a 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 high operational temperatures. More research work is necessary so as to increase the operational temperature of now 50 per cent of the alloy's solidus temperature, up to 90 per cent.

ODS-variants of Ni-base alloys and Fe-base alloys feature operation temperatures up to 90 per cent of their solidus temperature without creeping. However, Ni-base alloys need oxidation protection coatings at temperatures exceeding 1,000° C. Fe-base, ferritic alloys show a superior oxidation behaviour up to 1,250° C, but lower admissible loads compared to Ni-base ODS. Nevertheless, both types of ODS-alloys possess a high potential for the improvement of the efficiency of thermal engines. The drawback for high-temperature applications is the limited design potential as compared to cast components due to the mechanical alloying and PM HIP route. Nevertheless, the Fe-base alloy 1993, PM2000 is now used for serial high-temperature components of automotive engines. Research work is being 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 under way in the fields of metal alloys in order to improve the ecological situation of man-made technology. However, the driving forces of these developments are a mixture of political, economical and ecological factors. The main research and development domains are: the reduction of weight for transportation systems on ground and in air; the increase in 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 need only generally improved materials. With increasing technical demands for the components, tailor-made materials for 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 solidification are being investigated in order to obtain new alloys with new properties. An example is the Li-supersaturated AlLi-alloy, with a decreased specific weight. On the other hand, more complex loads, like the combination of thermal, mechanical and chemical load, in addition to the light-weight demand, lead to the necessity of specially designed materials compounds, consisting of different types of materials. However, the combination of different materials often produces drawbacks in materials properties and processing. For example, oxide dispersion strengthening improves the creep behaviour at high temperatures, but deteriorates the room temperature properties. Metal matrix composites (MMCs) exhibit higher stiffness, and thus an advantage in weight, but low fracture toughness and damage tolerance. Ductile phase toughening of brittle aluminides is metastable due 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 the separation of the materials. 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 when 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 an improved environmental compatibility. On the other hand, too high materials or product costs affect their competitiveness.

The above-mentioned results show that in many cases an appropriate materials solution for the respective technical problem can be achieved in the 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 the 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 raw materials mining and transportation to the complete production process, is undoubtedly necessary.

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Table 1. Greenhouse reagents and sources

Hothouse gases	Ejection of hothouse gases	Mean existence time	Share in additional hothouse effect in %	Relative hothouse potential*
Carbondioxide 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 years	13	58
Ozon O_3	Traffic	2-3 months	7	1800
Dinitrogenoxide N_2O	Manure, combustion of fossile energy resources	130 - 150 years	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, 1/1994, p. 68

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

	R_m (MPa)	$R_{p0,2}$ (MPa)	$R_{d0,2}$ (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 3. Typical application fields of 2xxx and 7xxx series alloys in aircraft

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 4. Applications of intermetallics in gas turbines

Component	Intermetallic	Temperature
High-pressure compressor	TiAl	650°C
• housings	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 5. Chemical composition and properties of a hot-rolled, micro-alloyed high-strength steel (QStE500TM)

alloying elements in wt%						
C	N	Mn	P	Al	Nb	V
0,07	0,006	1,3	0,01	0,04	0,045	0,045

mechanical properties		
YS	UTS	e_{80}
612	671	25

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

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 7. Variation of alloying elements in dispersion-strengthened aluminium alloys

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

Table 8. Classification of high-strength 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 9. Prealloyed P/M 7093 vs. ingot 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·m$^{1/2}$ (ksi·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 10. Overview of reinforced light-weight 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 11. Influencing parameters on a particulate reinforced MMCs' properties

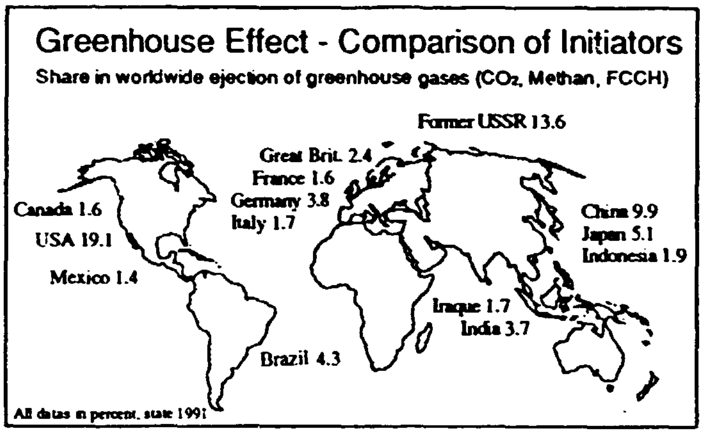
A: Type of Reinforcement	B: Production	C: Operating Condition
Particle material (e.g. Al_2O_3, SiC)	Raw material production, Solidification	Load type
Particle shape (e.g blocky, globulitic)	Hot-Working of the material (e.g extrusion, sintering)	Load direction
Particle size (typical: 10-30 µm)	Heat-treatment	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 12. Typical properties of P/M MMCs (extruded)

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/cm³ (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

Figure 1. World-wide initiators of greenhouse gases



source: Suddeutsche Zeitung 8.4.95

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

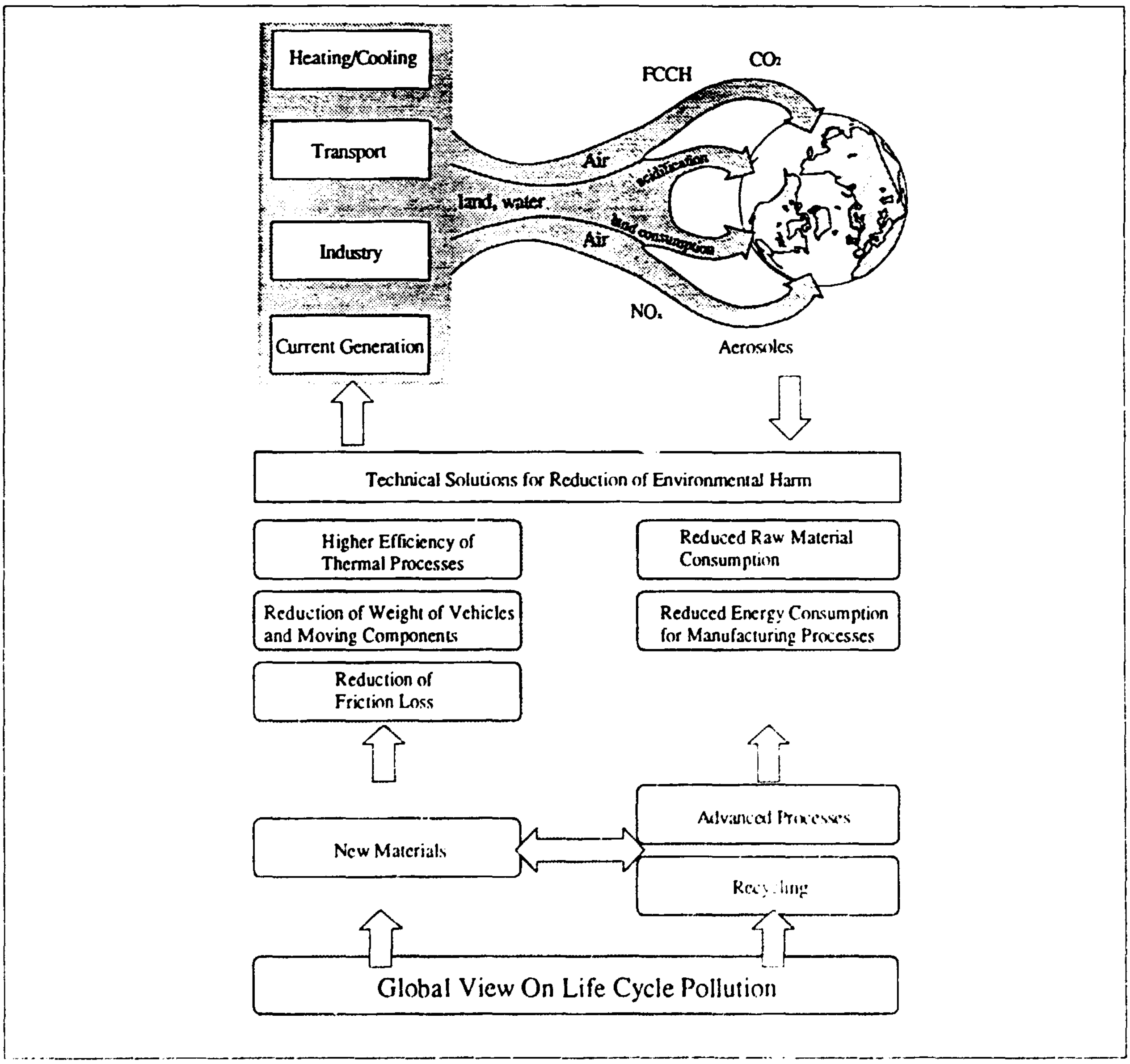


Figure 3. Reduction of weight and cost development

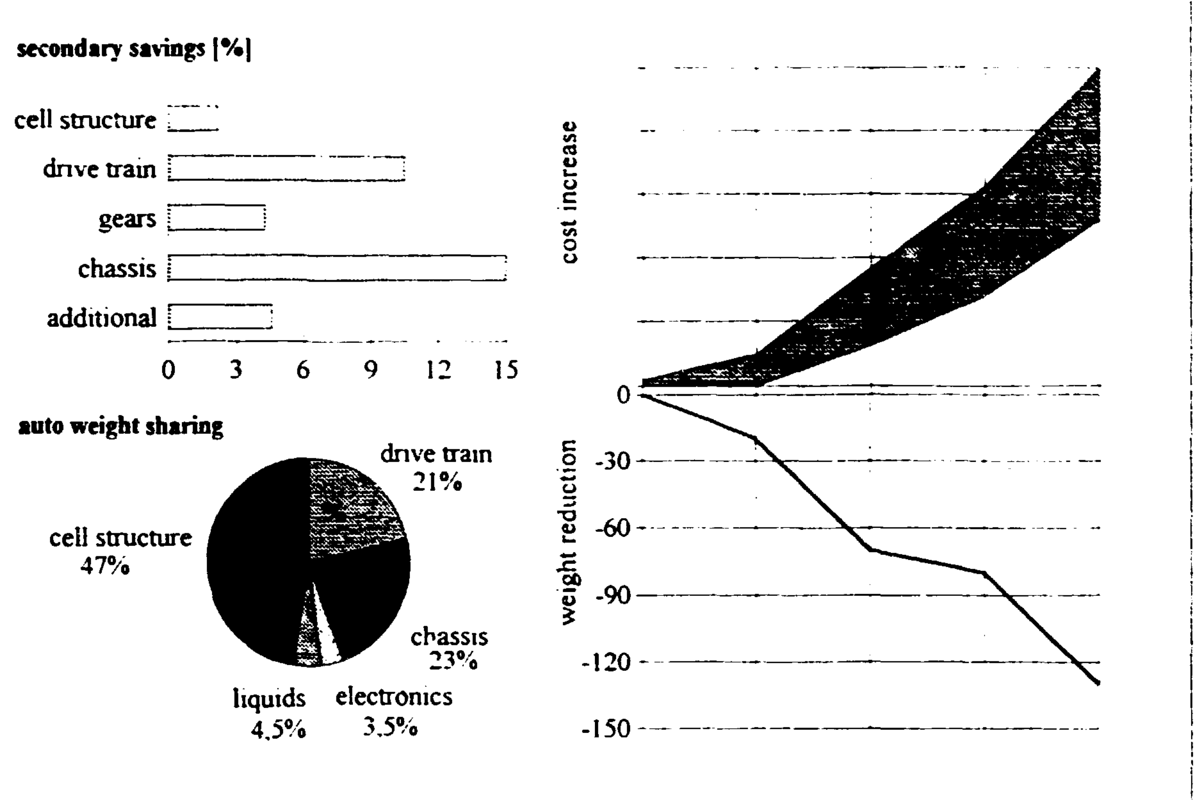


Figure 4. Light-weight construction concepts for a lorry

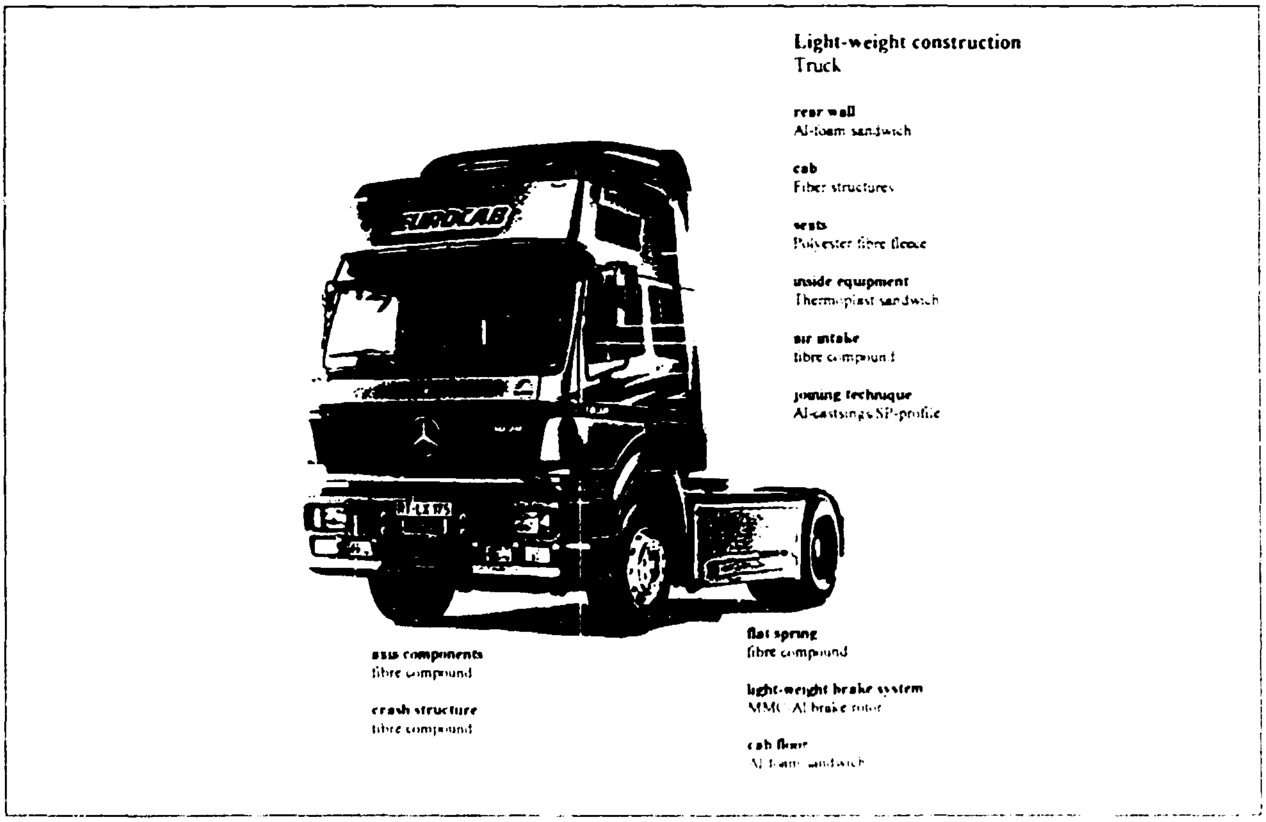


Figure 5. Property efficiency attributes of magnesium compared to those of selected other structural materials for auto applications: (a) Relative strength-to-weight ratio; (b) Elastic modulus; (c) Relative stiffness-to-weight ratio

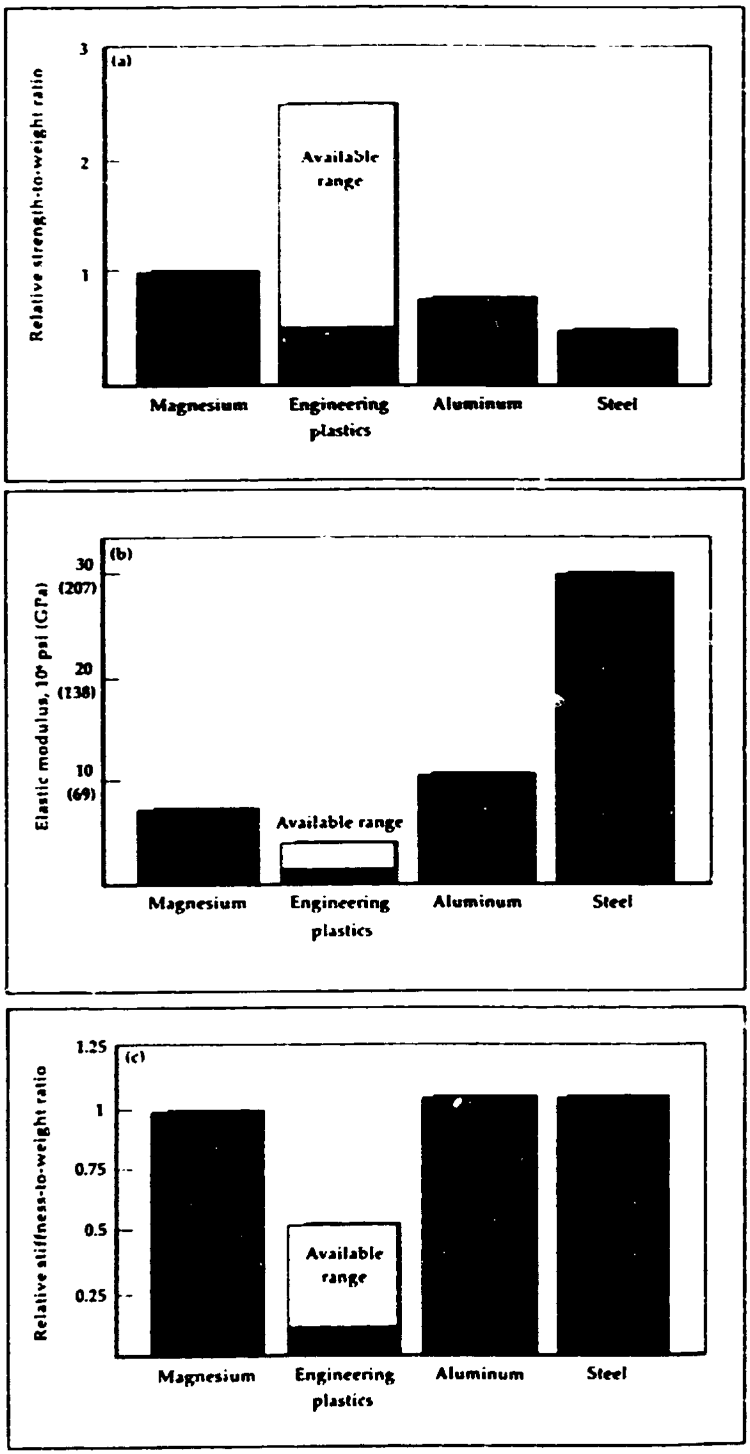
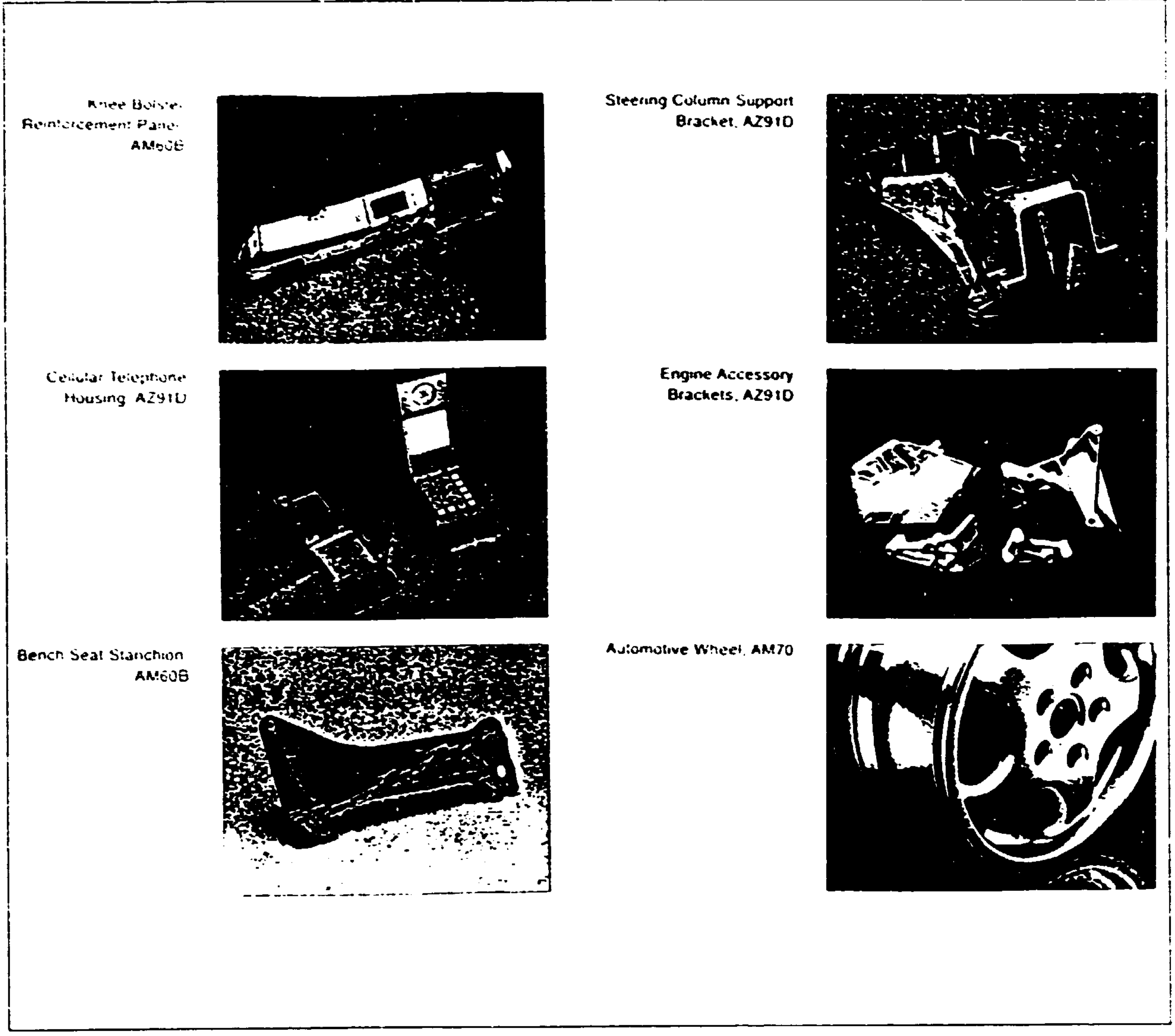


Figure 6. Typical magnesium applications



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 7. Material choice in light-weight structures

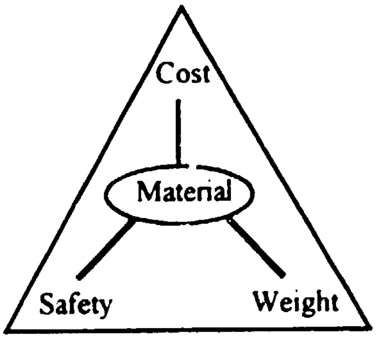


Figure 8. Content of different materials in aeroplanes

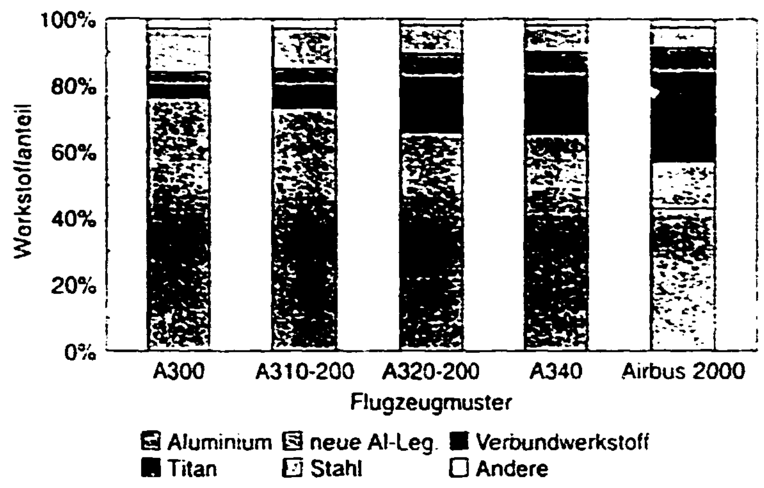
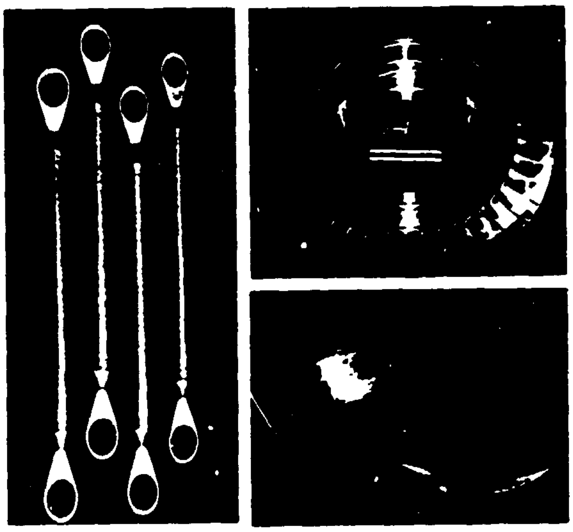


Figure 9. Components made by the use of long-fibre reinforced titanium



Nozzle, compressor and fan components

Figure 10. Aircraft panel: A typical application for long-fibre reinforced aluminium

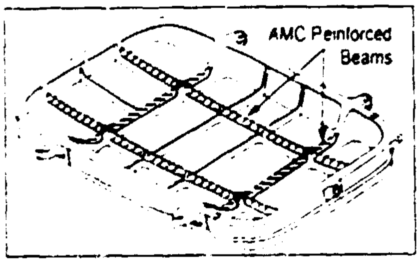


Figure 11. Critical piston sections[19]

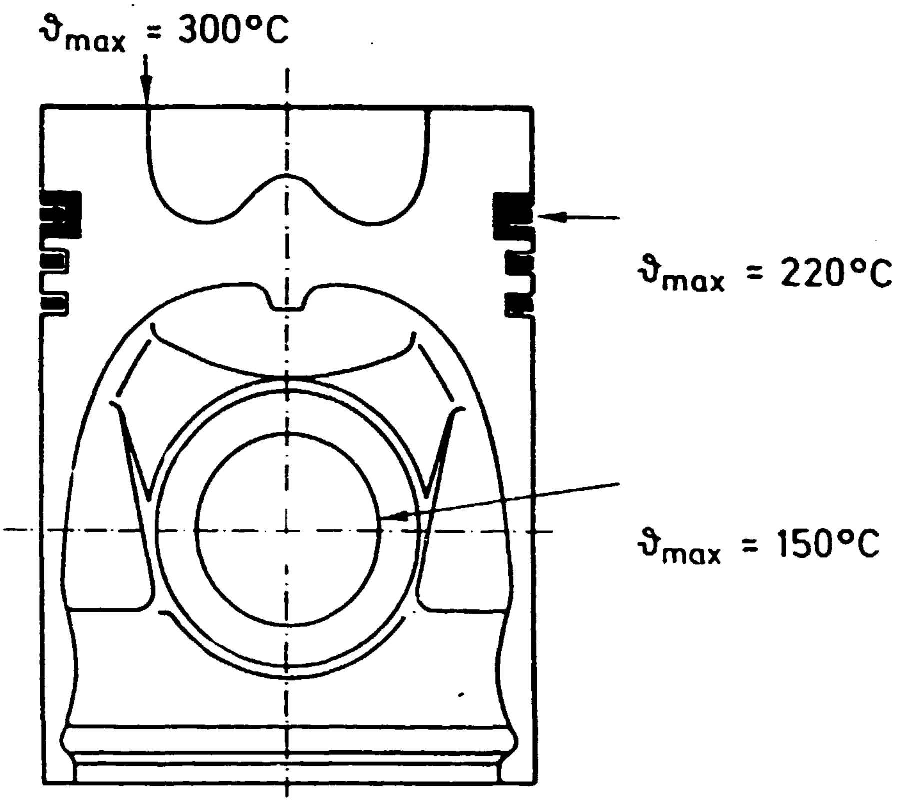


Figure 12. Required spring force of serial motors (related to the nominal rate of revolutions (6,250 1/min)[20]

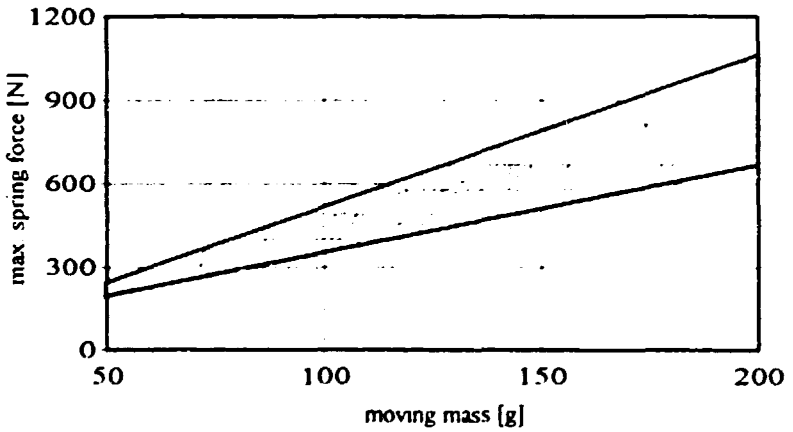


Figure 13. Reduction of fuel consumption with decreasing valve spring force (ECE-cycle)[20]

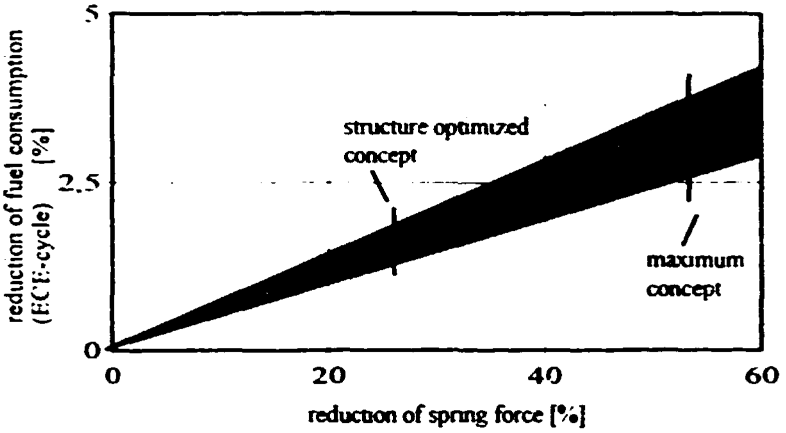


Figure 14. Masses of inlet valves[20]

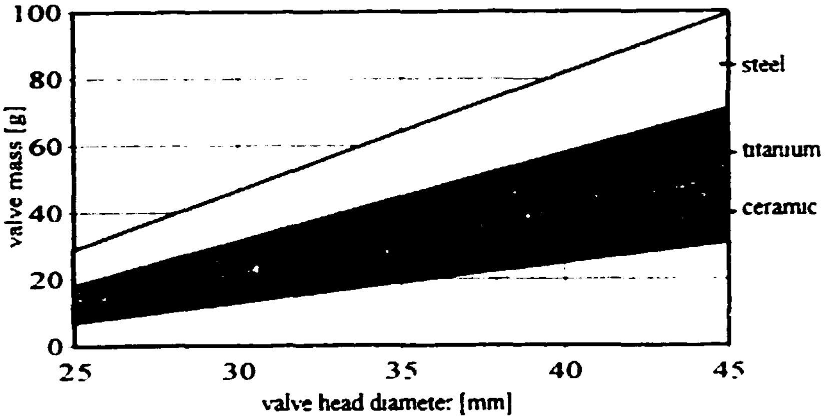
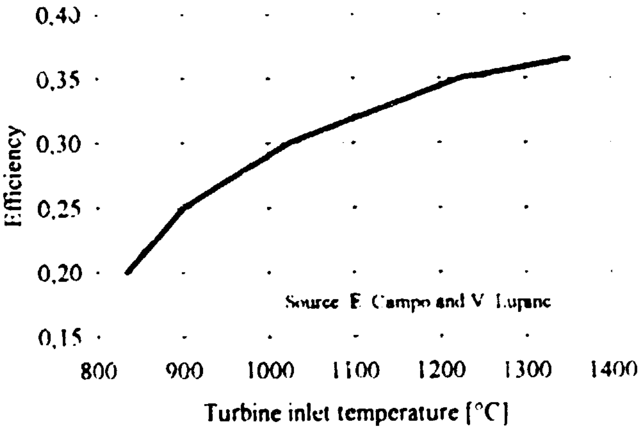


Figure 15. Increase in thermal efficiency with increasing gas temperatures at turbine inlet[24]



Source: E. Campo and V. Lupinc

Figure 16. FMW 701F first stage airfoils geometry: (a) Nozzle guide vane, and (b) Blade[24]

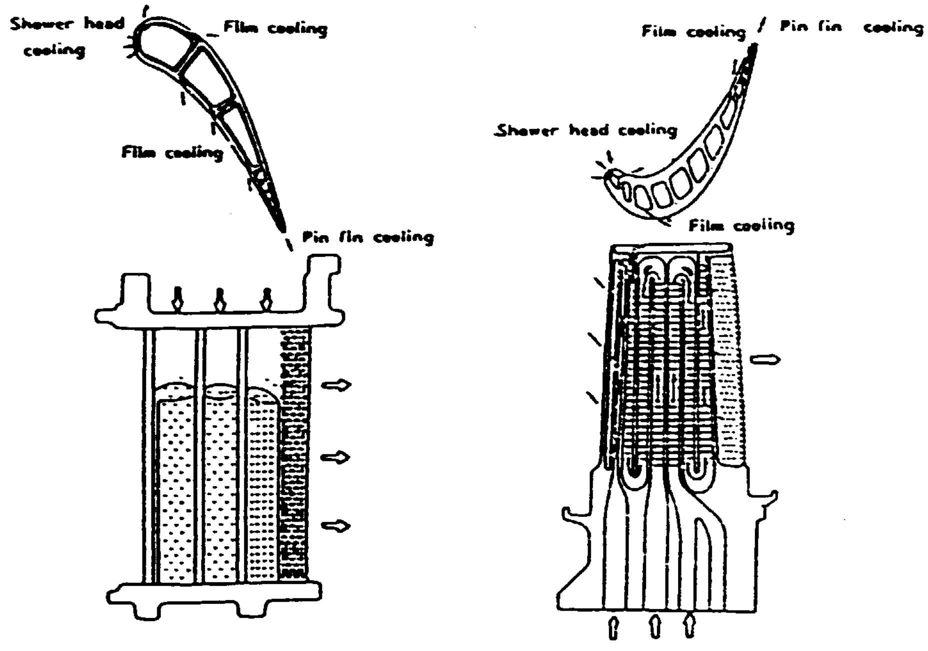


Figure 17. Application potential for intermetallic structural materials in gas turbines[24]

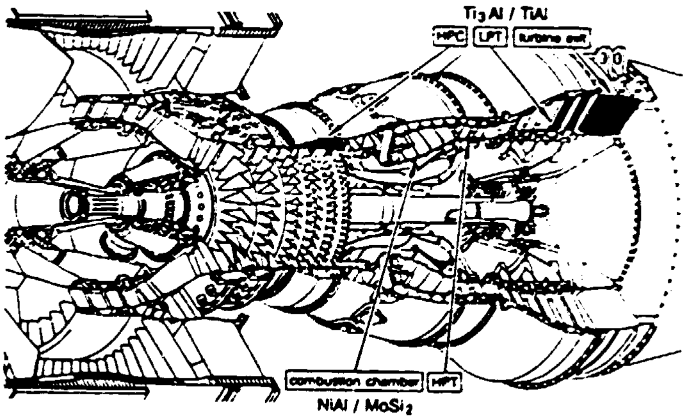


Figure 18. Weight reduction as a function of yield strength. Comparison between auto body structures (BH-steels) and crash elements (micro-alloyed resp. P-alloyed steels)[32]

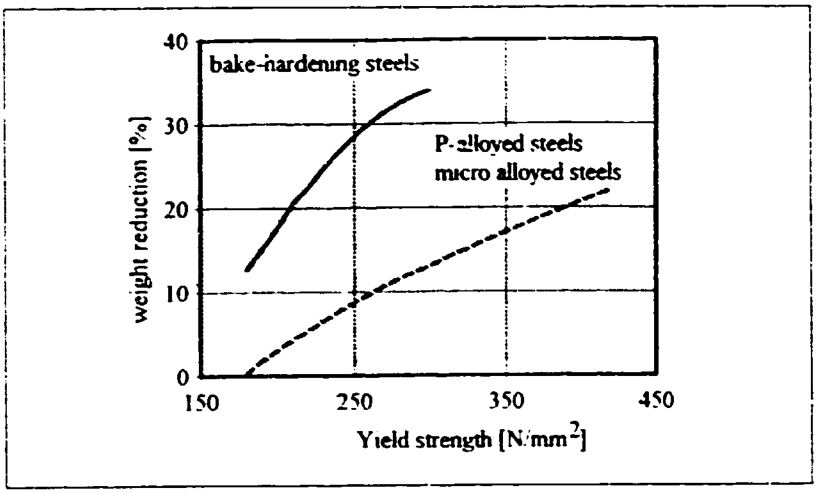


Figure 19. Increase in use of high-strength steel strips in automotive industry[30]

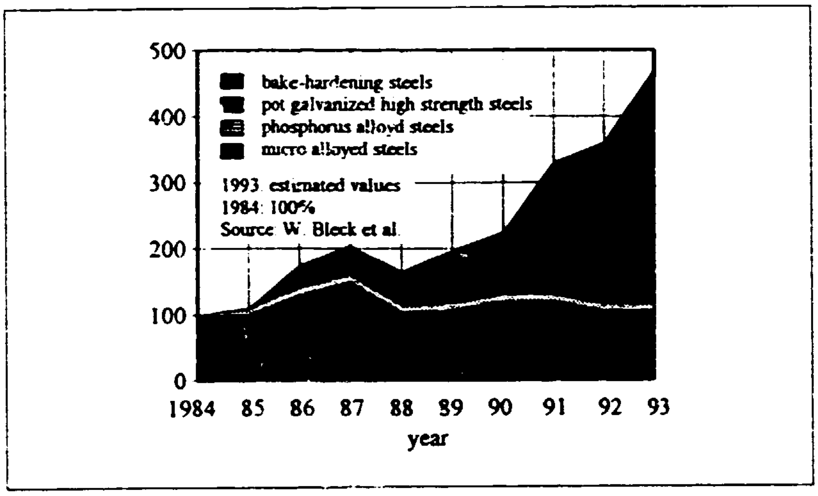


Figure 20. Dissipated specific energy of high-strength steels during dynamic room temperature tests as a function of the strain rate[31]

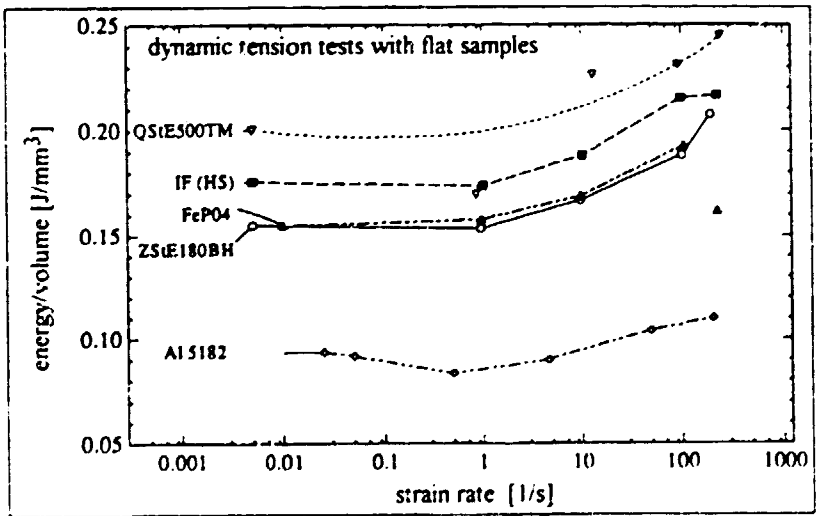


Figure 21. Flow stress of bake-hardening steels compared to steel St14[30]

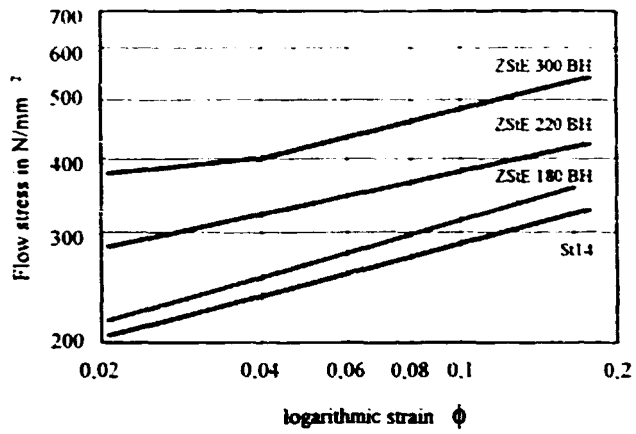


Figure 22. Influence of temperature and time on the bake-hardening effect BH0 (without pre-deformation) and BH2 (2 per cent pre-deformation)[29]

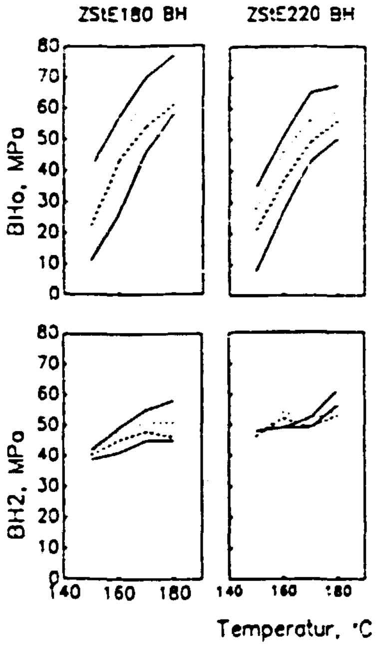
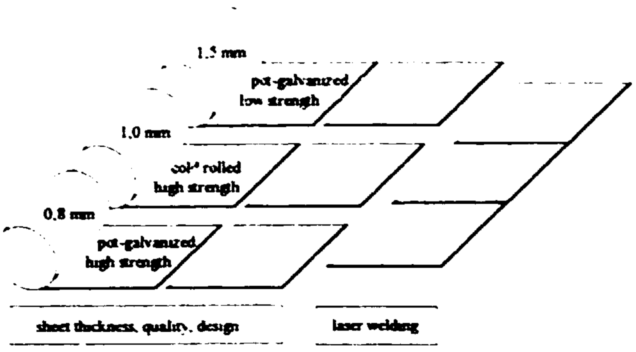
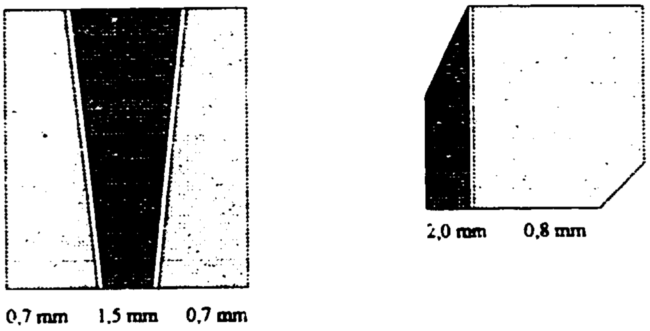


Figure 23. Schematic description of the production of tailored blanks[32]



source: Thyssen

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



bottom sheet

inner door sheet

source: Thyssen

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

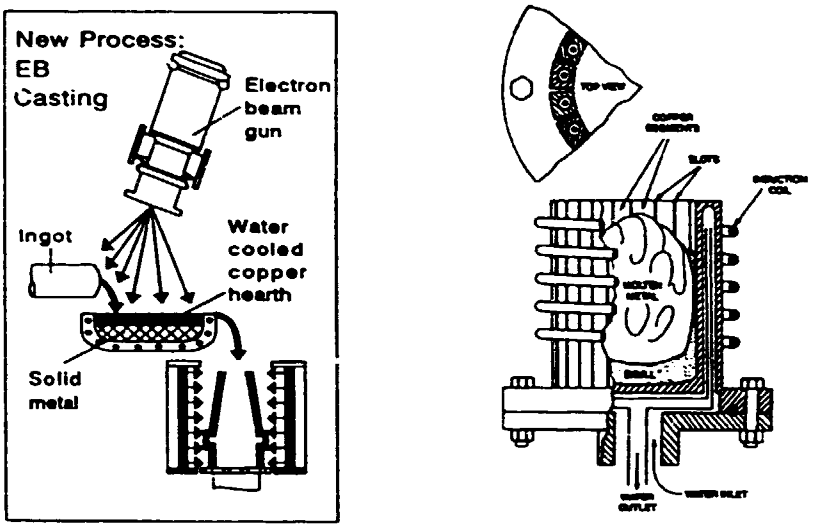


Figure 26. Comparison of conventional cooling and liquid metal cooling during directional and single crystal solidification[23]

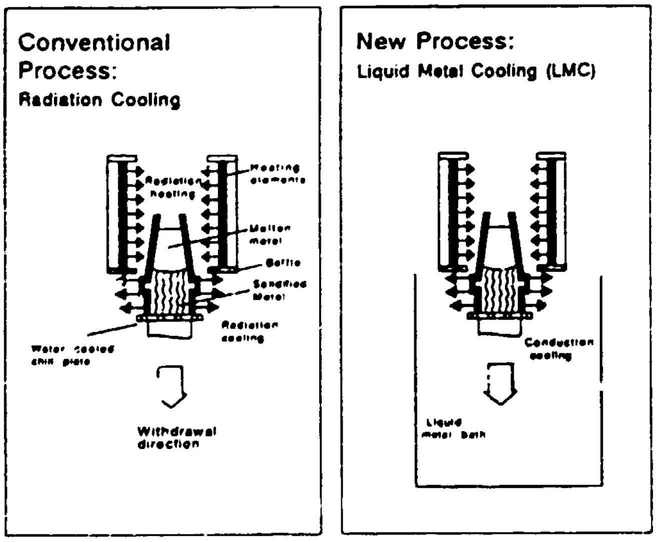


Figure 27. Maximum operation temperature of Ni-base alloys as a function of Cr-content. The temperatures are defined by creep resistance. The values are related to the creep strength of Ni-base alloy[23,33]

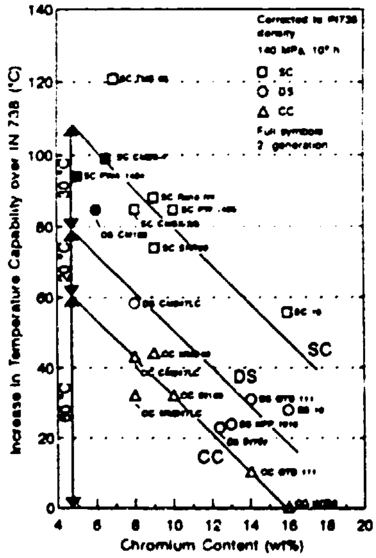


Figure 28. Room temperature fractures toughness K_{IC} of TiAl-alloys compared to Ni-base alloy IN738LC and Ti-alloy IMI834[24]

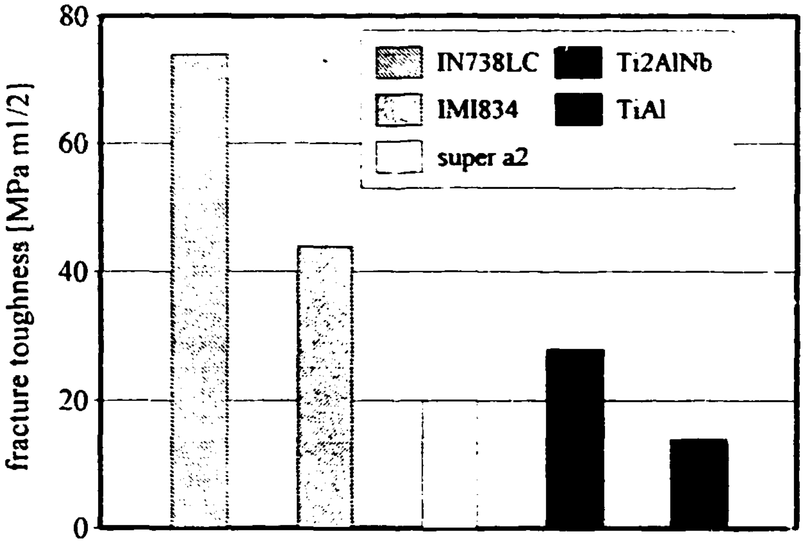


Figure 29. 0.2 per cent yield strength of Ti_3Al as a function of temperature compared to conventional Ti- and Ni-base alloys [Kumpfert, J., *et al*]

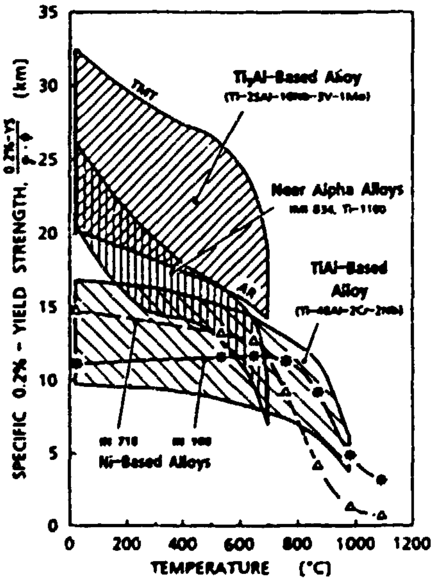


Figure 30. Oxidation behaviour of titanium alloys[37]

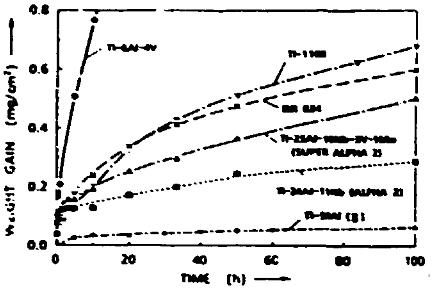


Figure 31. 0.2 per cent proof stress of NiAlCr as a function of temperature and Cr-content[36]

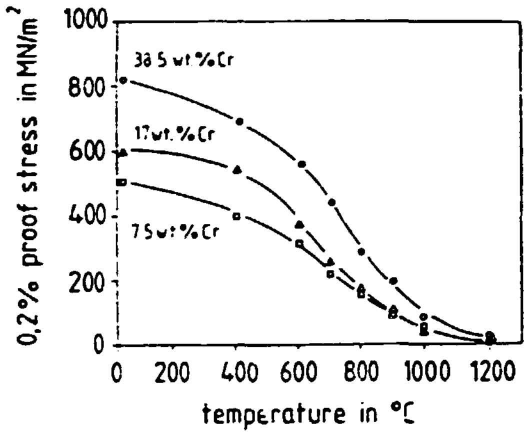


Figure 32. Temperature dependence of elongation and fracture toughness of NiAl-38,5Cr processed by HIP or HIP and extruding[36]

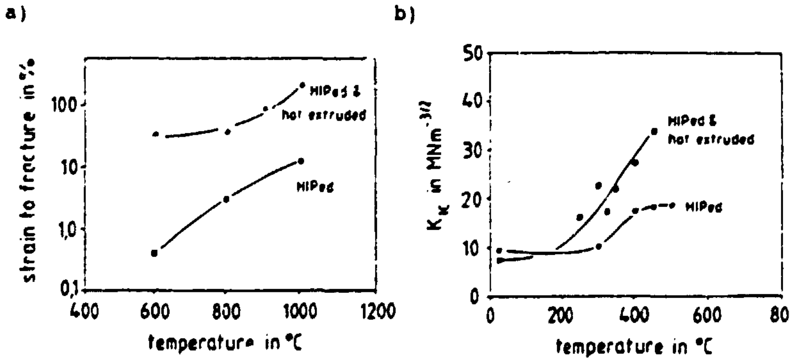


Figure 33. Youngs modulus and 0.2 per cent yield strength of Mg-Mg_2Si as a function of temperature[44]

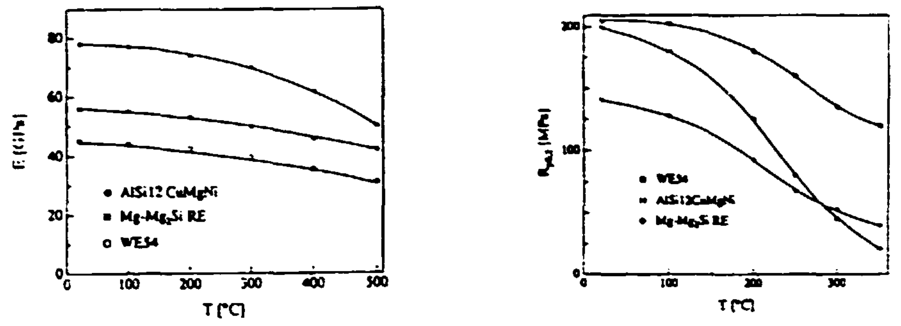


Figure 34. Coefficient of thermal expansion of different Mg-Mg_2Si alloys as a function of temperature, compared to standard piston alloy[18]

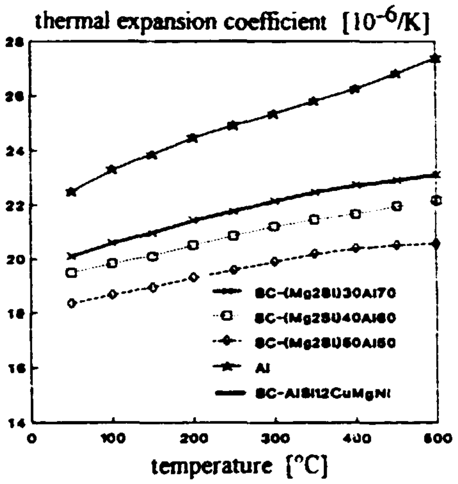


Figure 35. Proof stress of ODS-Al as a function of temperature, compared to Al7475 [Raufoss Inc., Norway]

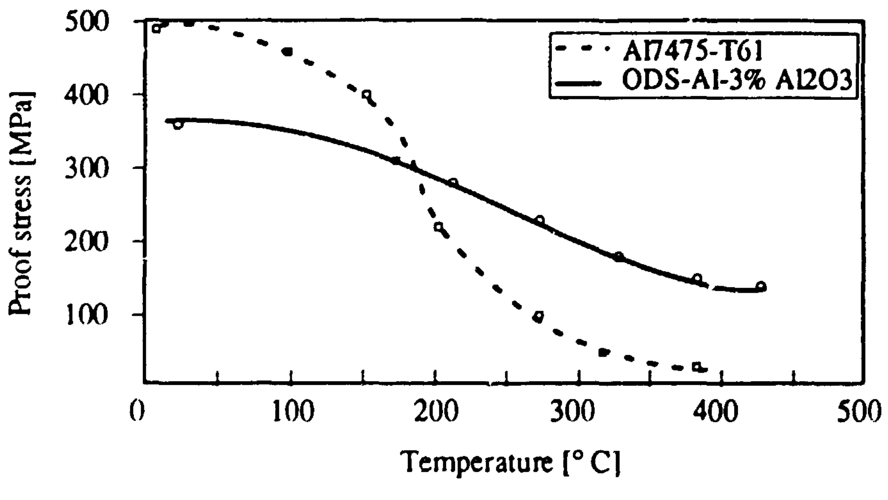


Figure 36. Creep behaviour of ODS-Al (Al + 3 per cent alumina) [Raufoss Inc., Norway]

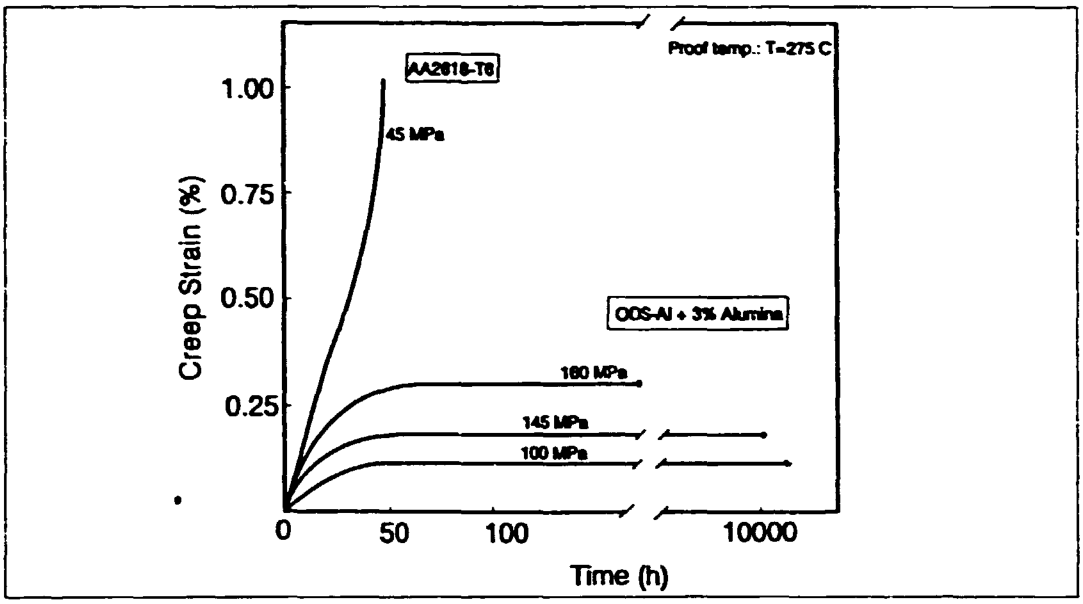


Figure 37. Ultimate tensile strength and elongation of different dispersion-strengthened Al-alloys as a function of dispersoid content[50]

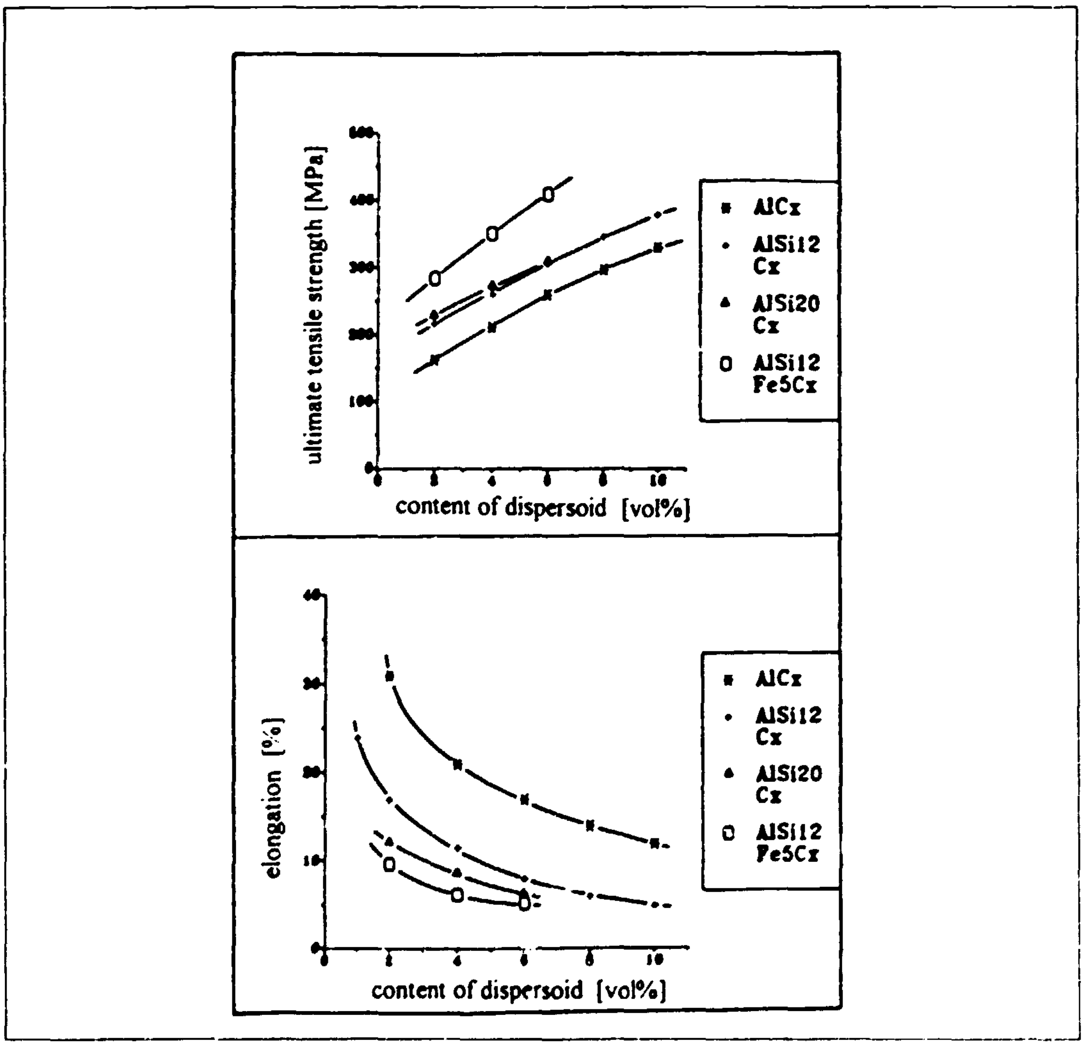


Figure 38. Ultimate tensile strength and elongation of different dispersion-strengthened Al-alloys as a function of temperature[58]

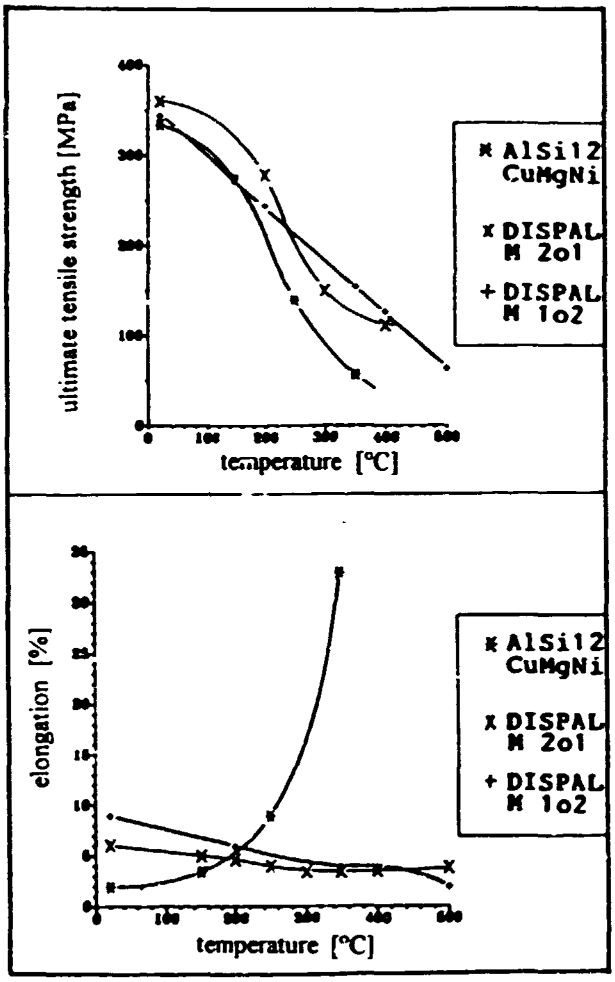


Figure 39. Creep behaviour of ODS-Ni-base alloy MA6000 as a function of temperature, compared to standard Ni-base alloys

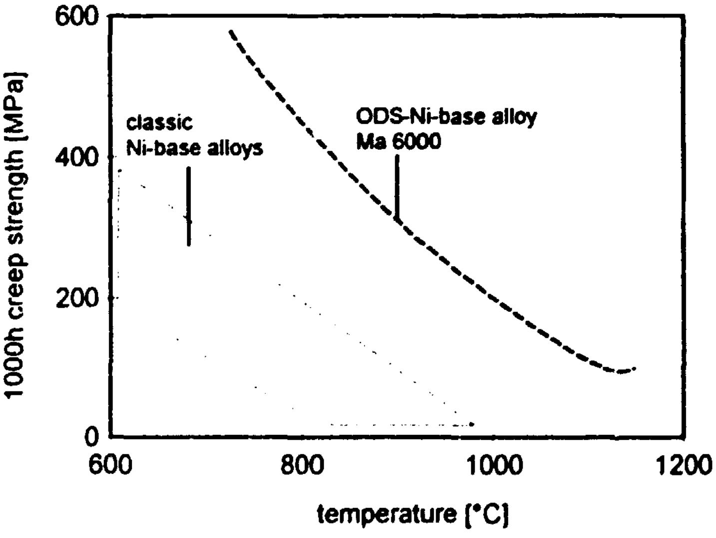


Figure 40. Creep behaviour of ODS-Fe alloy PM2000 as a function of temperature, compared to standard high-temperature alloys[54]

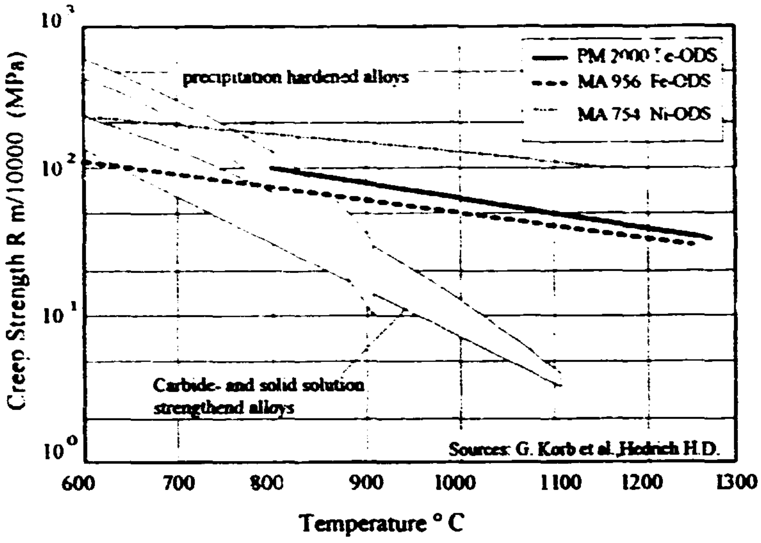


Figure 41. Increase of toughness as a function of the decrease of impurities for AlLi alloys

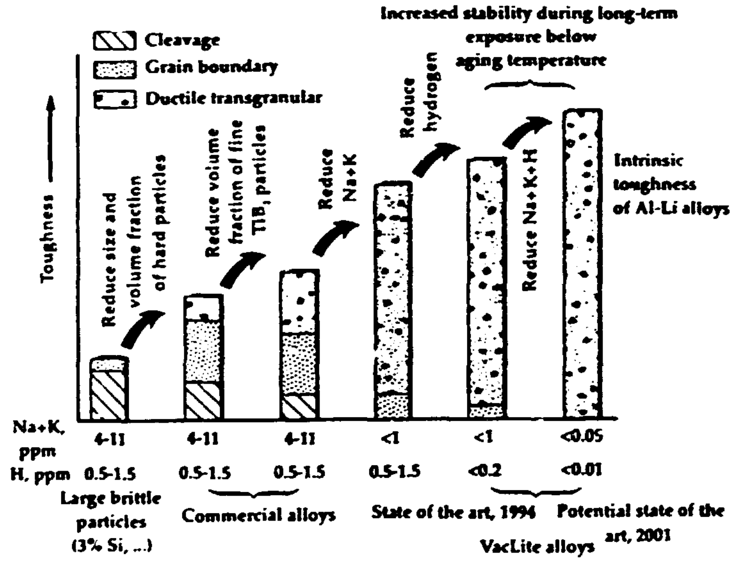


Figure 42. North American magnesium die-cast alloy consumption

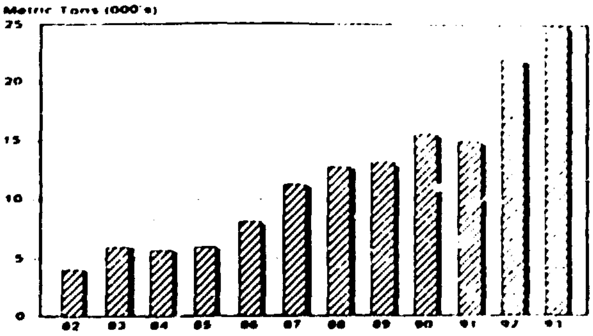


Figure 43. Properties of selected aluminium and magnesium alloys

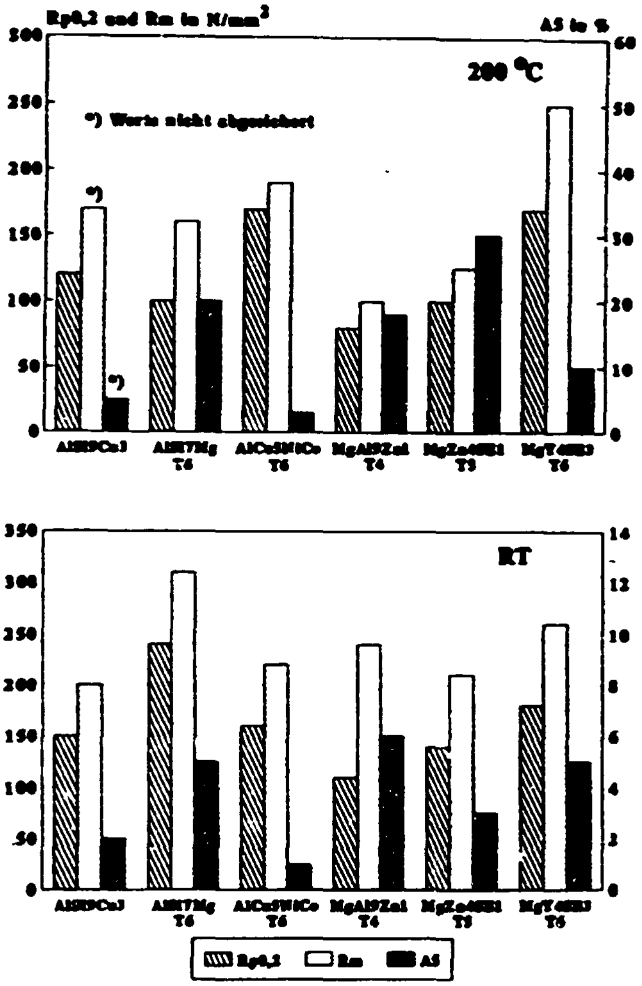


Figure 44. Magnesium alloy utilization trend 1994-1998

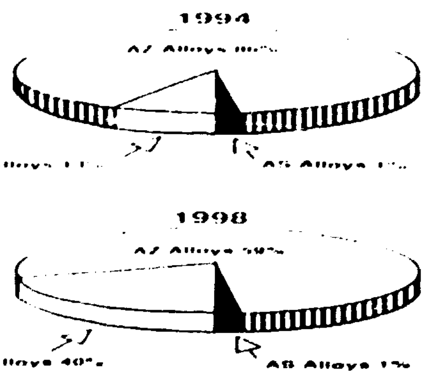


Figure 45. Powder-metallurgical production of particulate reinforced aluminium

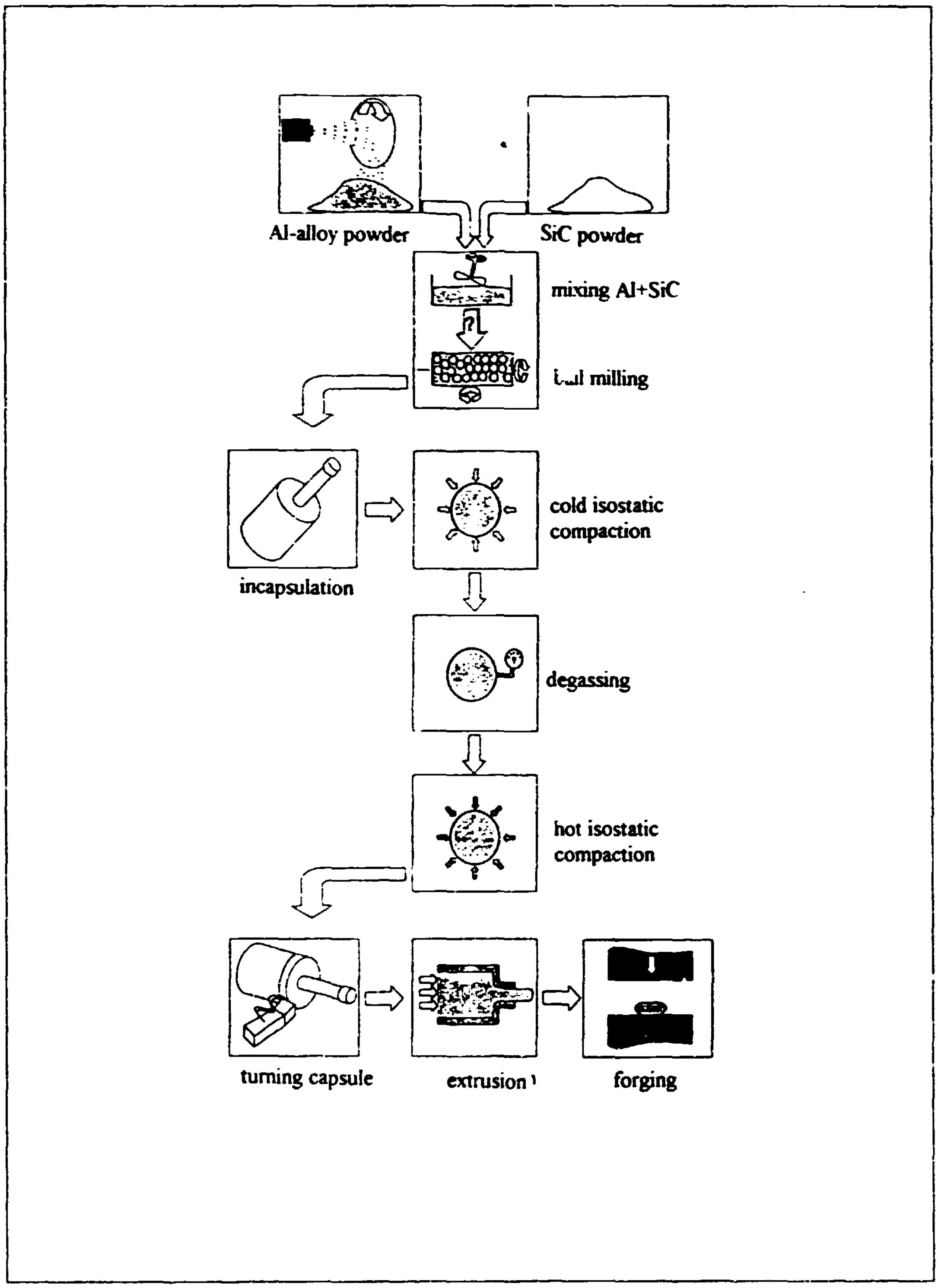


Figure 46. Typical properties of melt metallurgical produced particulate reinforced aluminium

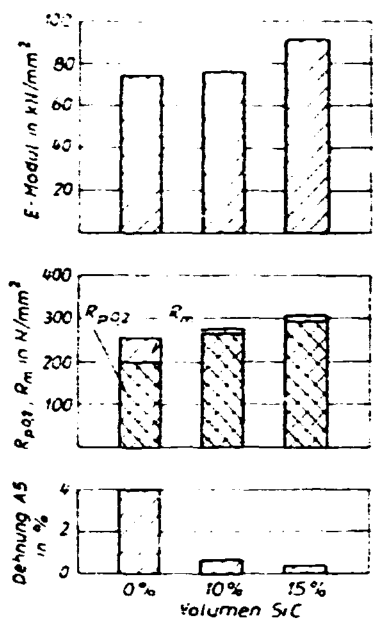


Figure 47. Comparison of the stress-strain behaviour of particulate reinforced aluminium alloys produced by different technologies. The 2024 alloy is not reinforced. PM means Powder Metallurgical, OSP means Spray Deposition (Osprey), Dur means Duralcan process (melt metallurgical)

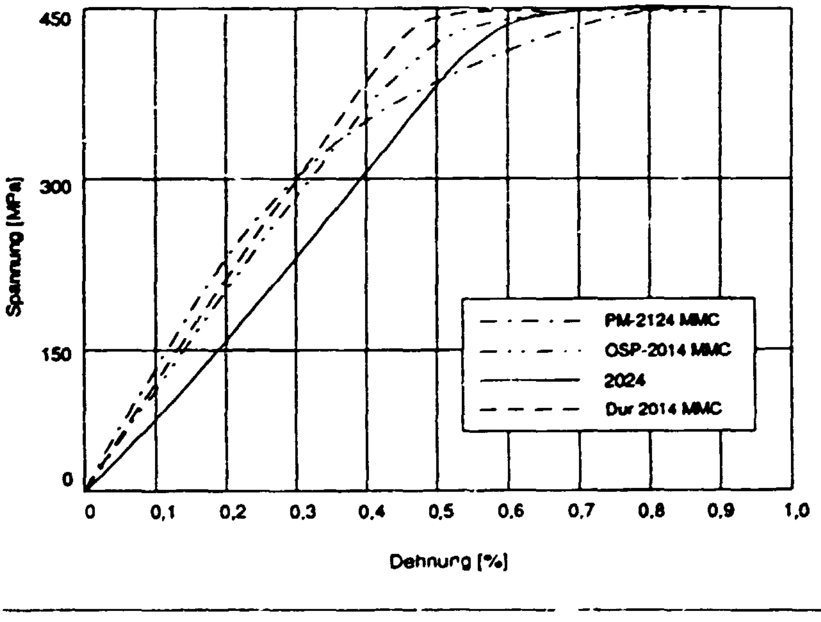


Figure 48. Weight loss vs. sliding distance for different particulate reinforced aluminium alloys

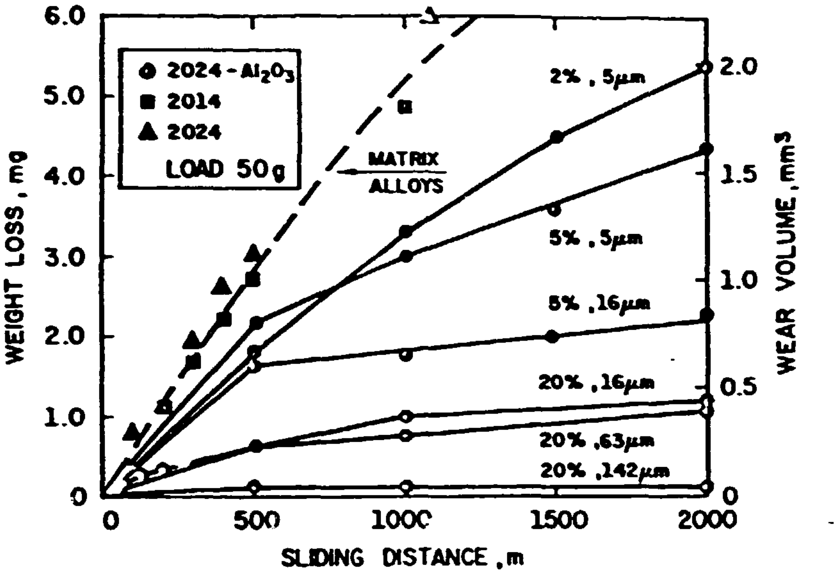


Figure 49. Specific modulus vs. specific strength for selected materials

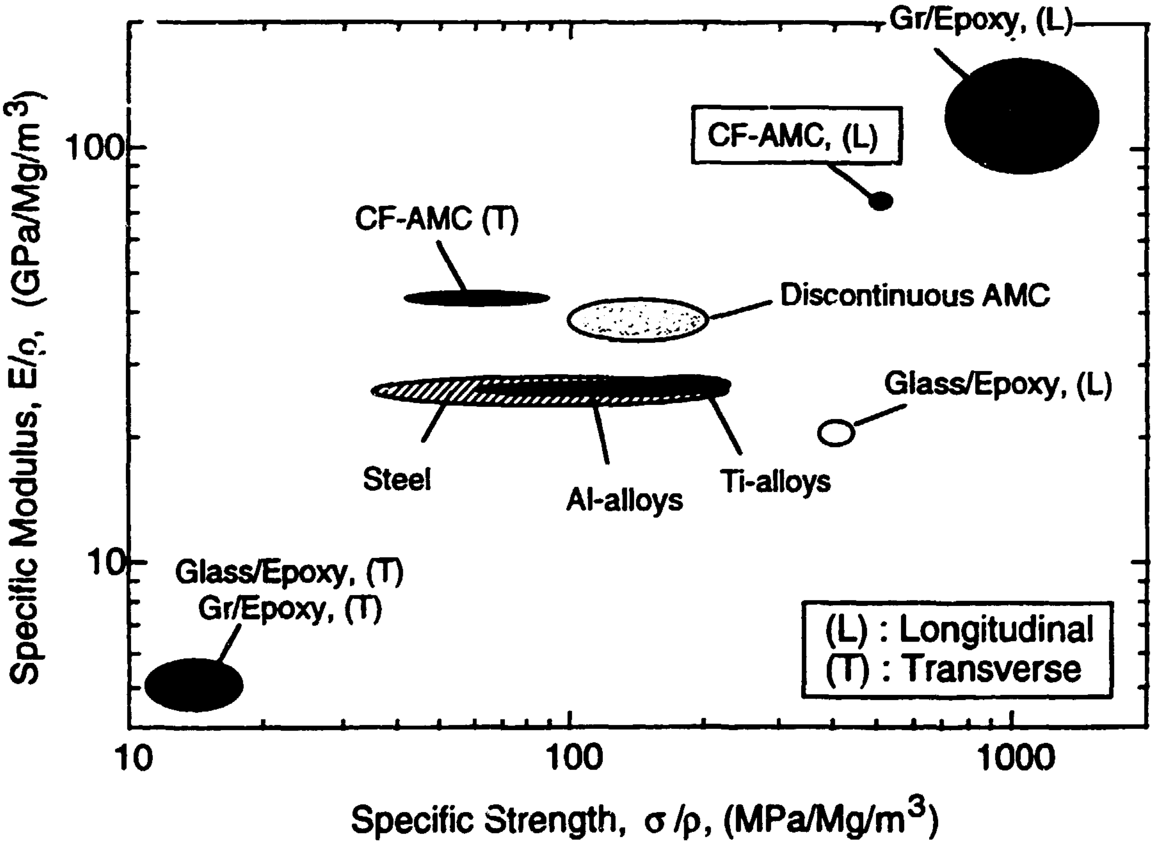


Figure 50. Life cycle of materials beginning with raw materials

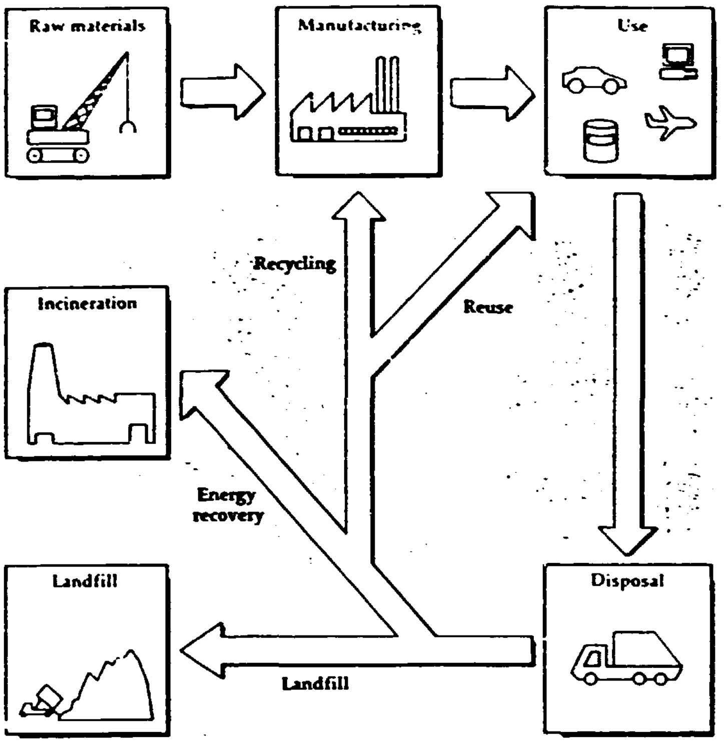
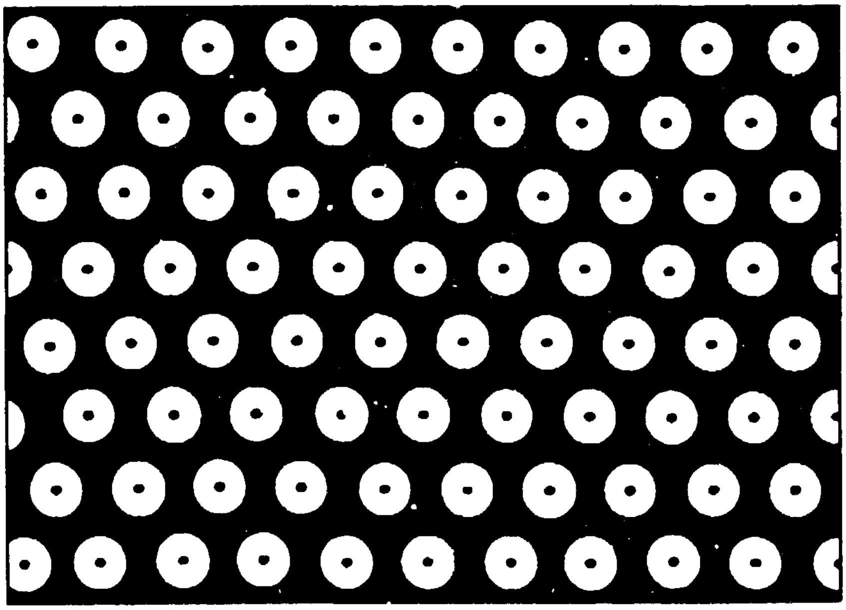


Figure 51. Cross-section of an SiC long-fibre reinforced titanium matrix composite



Abbreviations

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)

1. ALLOYS FOR SEVERE ENVIRONMENTS

Corrosion control with new nickel-base alloys

Nickel plays an important role in many of the alloys developed to withstand corrosive process environments such as those in the chemical, petrochemical, power, marine, and pulp and paper industries. Nickel imparts excellent corrosion resistance, toughness, metallurgical stability, and fabricability to alloys which contain iron, chromium, tungsten, as well as other metals. These alloys are valuable in processes with high concentrations of corrosives and high operating temperatures.

Tests have shown that in order to achieve the highest durability in corrosive aqueous environments, alloys require high concentrations of both chromium and molybdenum, together with additions of tungsten and or copper. A suitable balance of these metals is maintained in the Ni-Cr-Mo-W family of alloys, enabling them to resist aqueous corrosion, contaminated phosphoric acid, various oxidizing and reducing chemical environments, acid chlorides and sea water. Alloy G-30 is a good example, being used in the wet-process production of phosphoric acid, because none of the conventional stainless steels or nickel-base alloys containing <9 per cent Mo provide acceptable corrosion resistance, especially when the process liquor is contaminated with chlorides and fluorides. This alloy finds further uses in reheater tubes, agitator blades, pump components and reboilers in nuclear waste reprocessing, as well as a range of components in pulp and paper plants.

The alloy 625 was developed for high-strength, high-temperature aerospace applications, but it exhibits outstanding resistance to a variety of acids, chloride pitting crevice solutions, stress-corrosion cracking, and fatigue. Since its initial development, three new versions have been developed by companies in the United States of America. The 625 Plus is an age-hardenable alloy having almost twice the yield strength of alloy 625 with similar corrosion resistance. Screening tests for sour gas well applications showed that it was as resistant to sulphide stress-corrosion cracking as alloys 625 and 718. The Inconel alloy 725 offers similar properties.

Stress-corrosion-cracking resistance was evaluated in high-temperature, high-purity-water tests developed by the nuclear power industry. The 625 Plus alloy is equal here to alloy 625, and better than alloy X-750. Hence, both 625 Plus and 725 are good candidate materials for applications in deep sour gas wells, refinery environments, aggressive aqueous chemical solutions, and nuclear power plants.

The third version, alloy H-9M, was developed to provide exceptional corrosion resistance at a lower cost than 625 and C-276, through increasing the amount of iron, reducing the nickel content and increasing the molybdenum and tungsten components in the alloy as compared to alloy G-30. The new alloy displayed excellent corrosion resistance during a three-year test in a power plant's sulphur-dioxide scrubber and ducting. As a result, it is being further evaluated for other applications, as well as for components for the oil and gas industry.

Even though alloys 625 and C-276 have for a long time been the most corrosion-resistant alloys available to the chemical process industry, several new alloys have been introduced. These new variations (Hastelloy alloy C-22, Nicrofer alloy 59, and Inconel alloy 686), all offer outstanding resistance to localized corrosion, maintain metallurgical stability, and are not sensitized during heating or welding. In addition, welding filler metals which are basically equal to the base metal are available for these alloys, thus improving resistance to aggressive corrosive environments. Applications are in outlet ducting and stack liners of power plant sulphur-dioxide scrubbers, pulp and paper mill bleach plants, and chemical process plants.

A further new nickel-base alloy for aqueous corrosion environments is alloy 690. The doubling of the chromium content resulted in excellent corrosion resistance in highly oxidizing acids and high temperature environments. The high nickel content enables it to resist stress-corrosion cracking in hot water, chlorides, and caustics. As a result alloy 690 has become the replacement alloy for retubing steam-generator components. It was also selected for vitrification-furnace electrodes and off-gas ducting systems for the disposal of nuclear wastes. It is further used in heating coils and tanks for nitric HF accid solutions in the pickling of stainless steels and the reprocessing of nuclear fuels.

Heat-resistant alloys must maintain corrosion resistance, mechanical strength, metallurgical stability, creep resistance, stress-rupture strength, and toughness at temperatures greater than 425° C. The chromium content is most important for oxidation resistance; additions of cobalt, aluminium, silicon, and rare earths all enhance the formation, stability, and tenacity of the oxide surface layer. Nickel provides the strength, stability, toughness and carburization resistance, whilst tungsten and molybdenum increase the high-temperature strength.

These new high-temperature alloys generally contain high levels of chromium and cobalt, which may not be necessarily available everywhere. The alloy 253MA was thus developed to try and provide the same properties, but using other elements. It maintains structural stability and creep strength and provides oxidation resistance similar to types 310 and 446 stainless steels, by replacing some of the chromium with silicon and rare-earth metals. The cobalt-free alloys 214, 230 and 556 all offer oxidation resistance, as well as resistance to environments containing sulphur, chlorine, nitrogen, carbon, chlorides and molten metals.

For sulphidizing atmospheres, alloys 188 and 556 appear, at present, to be two of the best alloys available. Their excellent sulphurdation resistance is primarily due to their low nickel content, cobalt additions and the high level of chromium.

Other high-temperature conditions of interest are molten salt and molten zinc. In molten salt tests, alloys 188 and 556 provide the best resistance, followed by alloy 214, Type 304 stainless steel, and Type 310 stainless steel. Similar trends appeared in tests conducted in molten zinc at 450° C.

Results from corrosion tests of alloys in 760° C flue gases from an incinerator burning mixed acid wastes, showed that alloy 556 provided the best corrosion resistance. Recent laboratory tests for the new alloy from Haynes, alloy HR-160, showed that it formed a highly protective surface oxide scale which resisted attack from sulphur, chloride, vanadium and other salt deposits.

All these high temperature materials are being used in metallurgicalprocessing, petrochemical,chemicaland waste incineration industries. Some examples include recuperators in waste heat recovery systems for blast furnace off-gases, styrene reactor tubes, waste incinerators, diffuser plates in a carbon regenerator furnace, and wire-mesh belts. (Extracted from *Advanced Materials & Processes* 7/94)

Superplastic forming of alloy 718

The Inconel Alloy 718 is available in a fine-grained, controlled composition modification that can be superplastically formed. The Inconel 718 was developed in the early 1960s and is a Ni-Cr-Mo-Nb alloy widely used in jet engine parts such as compressor and turbine disks and rings, turbine shafts, exhaust sections, hot air ducting, and fasteners. The new superplastic forming (SPF) capability allows the manufacture of large, complex, and detailed parts, improving integrity by reducing the need for joining. In addition, it allows designers to fabricate components having higher strength, fatigue resistance, and temperature capability than parts made of aluminium or titanium alloys.

The nominal composition of alloy 718SPF is 50-55 Ni, 17-21 Cr, 4.8-5.25 Nb, 2.8-3.3 Mo, 0.65-1.15 Ti, 0.2-0.8 Al, 0.35 Mn, 0.03 C, 0.015 S, bal Fe. It is made by vacuum induction melting and electroslag remelting. It is conventionally hot-worked, then cold processed using proprietary technology to make a sheet product. Although chemistry modification was not needed to produce the fine microstructure needed for SPF, the maximum carbon and niobium contents have been reduced to minimize carbide precipitation during part manufacture. The grain size is sufficiently stable at processing temperatures of 980° C, or less, to ensure adequate time for SPF. This fine-grained condition is achieved through alteration of conventional cold rolling and annealing practices, and has been found to dramatically boost fatigue resistance as compared with the conventionally produced alloy 718.

Several aerospace companies are showing interest in alloy 718SPF, applications are expected to grow over the next few years as designers and SPF-processing companies become familiar with the material. (Extracted from *Advanced Materials & Processes 4/94*)

Titanium-niobium alloy solving autoclave problem

Certain gold ores and concentrates, zinc concentrates, and nickel mattes (sulphide mixtures), can be effectively treated by aqueous pressure oxidation. Here a sulphide-containing pulp is leached under an oxygen sparge (oxygen injector), oxidizing the sulphide to elemental soluble sulphate ion, and liberating the metal. Gold-containing pyrite grains are converted to hematite (Fe_2O_3) and aqueous sulphate, liberating the gold. This reaction is generally carried out in autoclaves at approximately 200° C and several atmospheres of oxygen overpressure.

To enable survival in this severely corrosive environment, autoclave vessels are constructed of lead-lined steel, with two courses of acid refractory brick. However, materials specification is difficult for ancillary equipment such as oxygen injectors, impellers, and vent lines. Some nickel-base alloys and stainless steels have favourable ignition characteristics, but high corrosion rates that thus limit service life.

Titanium and zirconium alloys offer superior corrosion resistance in the oxidizing sulphuric acid environments present in sulphide pressure-leaching operations. The use of these materials is, however, somewhat limited because of their pyrophoricity, the tendency to ignite when exposed to oxygen at high temperatures. Materials selection has thus usually involved an unsatisfactory compromise among corrosion resistance, physical properties and oxygen compatibility. The titanium alloy Ti-45Nb appears to have suitable mechanical properties, a significantly reduced field of ignition characteristics, and corrosion resistance similar to that of Grade 2 titanium.

Investigations carried out at Teledyne Wah Chang (Albany, Oregon, USA), on ignition-resistant titanium alloys were initially based on models showing that ignition and combustion depend on heat of oxidation and thermal conductivity. Researchers presumed that because niobium has the lowest heat of oxidation among metals showing extensive solubility in titanium, it should be the most effective element for reducing pyrophoricity. The experiments showed that alloying with niobium substantially increases the threshold oxygen pressure for ignition at a given temperature, due not only to its low heat of oxidation, but also because of its high oxygen diffusivity. In addition, Ti-45Nb burns significantly slower than standard titanium alloys.

Laboratory tests also showed that Ti-45Nb does not ignite at pressure and temperature conditions under which Grade 2 titanium and other standard titanium alloys ignite. Further, test coupons placed in the vapour space of an operating autoclave for up to 180 days showed no measurable corrosion.

A field test of an autoclave steam vent line fabricated with Ti-45Nb has performed well. In 1991 a duplex stainless steel vent line was replaced with one made from Ti-45Nb. After six months service, ultrasonic inspection showed no loss in the sectional area of the vent line. The pipe is still in use, previously the stainless steel pipe had to be replaced yearly. This success has led to operators of other autoclave plants selecting Ti-45Nb for vents, oxygen dip pipes, and steam injectors.

Further experiments have been carried out whereby the researchers fractured titanium samples of various geometries in high-pressure oxygen mixtures over a range of temperatures. Studies have reported the high burn rates of titanium in specific situations, but not in connection with a systematic attempt to describe a set of ignition conditions. Research continues to find the mechanism responsible for the alloy's higher ignition resistance, as well as its apparent sensitivity to ignition at higher oxygen pressures. (Extracted from *Advanced Materials & Processes 5/94*)

Selecting the right stainless steel

Selecting materials that need to resist corrosion whilst providing high strength often means that the total life-cycle cost can become more significant than the purchase price. Additional costs for maintenance and replacement of a less expensive alloy may dwarf the initially higher price of a more suitable stainless steel. However, with so many grades available, both standard and proprietary, selection of the best stainless steel can be problematic.

The first step should be to determine the level of corrosion resistance needed for a specific application, the chemistry, temperature, and length of time spent in the operating environment. The most economical alloy should offer enough corrosion resistance to provide the required service life without the expense of over-alloying.

The selection process should start with the basic AISI Type 304, a stainless alloy in the middle range of corrosion resistance provided by stainless steels. This is austenitic and non-magnetic, and cannot be hardened by heat treatment; instead it must be cold worked to increase tensile strength. This alloy resists most oxidizing acids, many sterilizing solutions, most organic chemicals and dyestuffs, together with a wide range of inorganic chemicals.

For applications requiring a higher level of corrosion resistance, consider AISI Type 316. This has added molybdenum to boost its resistance to attack by many industrial chemicals and solvents. It can resist pitting caused by chlorides. It is specified to resist corrosive process chemicals used to produce inks, rayons, photographic chemicals, paper, textiles, bleaches and rubber, also being used for surgical implants within the human body.

For severe corrosive environments, consideration should be given to a stainless grade such as Carpenter's 20Cb-3. This is a highly alloyed proprietary grade which resists corrosion from sulphuric acid, particularly in high concentrations and at high temperatures. The small addition of niobium stabilizes it against loss of corrosion resistance due to intergranular attack, resulting possibly from welding. Further, it resists hundreds of common industrial and process corrodents, including acetate solvents, cadmium sulphate, ferrous sulphate, boric acid and zinc chloride.

In less-severe corrosive environments, ferritic AISI Type 430, which is less costly than 304, 316 and 20Cb-3, may be adequate. Type 430 is less resistant to corrosion than Type 304 as it contains no nickel and slightly less chromium, however, it effectively resists foods, fresh water, and non-marine atmospheric corrosion. Type 430 is often used for decorative trims on automobiles, appliances, and architectural hardware.

When only a minimum of corrosion resistance is needed, AISI Type 405 may be specified. This is a ferritic, low-cost stainless steel which resists simple corrosive attack by unpolluted atmospheres and fresh water. This was designed for use in the as-welded condition, often requiring no post-weld annealing treatment. The alloy resists corrosion from soap, sugar solutions, mine water, steam, carbonic acid, perspiration, ammonia, alcohol, crude oil, petrol, mercury, and other mild reagents.

Having specified the corrosion resistance requirements, the next stage is to identify the most significant mechanical property, usually strength. When selecting a stainless steel based on a mechanical property, consideration must also be given to how development of that property may affect corrosion resistance. For example, heat treating or cold working to increase strength may increase susceptibility to stress-accelerated corrosion.

Selection for physical properties should also be considered, particularly magnetic properties. For example, a 22Cr-13Ni-5Mn stainless steel, which is non-magnetic in all conditions, may be preferred to Type 304 stainless steel, which may become slightly magnetic when cold worked. Other considerations may include the material's hardness, impact resistance, fatigue strength or stress rupture resistance. If resistance to corrosion at the Type 405 level is adequate, but higher strength is required, the AISI Type 410 stainless steel could provide the service needed. This is martensitic, similar to Type 405, but with a higher carbon content and no aluminium changes in composition that improve its mechanical properties. It is especially useful in applications requiring good strength, ductility, and resistance to oxidation up to 650° C. Typical applications are highly stressed parts such as steam-turbine buckets and blades, or gas-turbine compressor blades.

When greater strength and hardness are required at the same level of corrosion resistance, consideration could be given to AISI Type 420. Its greater hardness makes it useful for wear-resistant applications such as surgical and dental instruments, cutlery, scissors, gauges, valves, gears, shafts, ball bearings and magnets.

The ultimate hardness at the lowest level of corrosion resistance is provided by AISI Type 440-C. This is thermally hardenable and martensitic and provides the maximum hardness from any stainless steel. The high level of carbon content means that it has the lowest level of corrosion resistance. Applications would include bushings, cutlery, valves and ball bearings which require the highest hardness.

Higher strength and increased corrosion resistance are provided by the group of nitrogen-strengthened, austenitic stainless steels. All five of these stainless steels have a strength level between Type 405 and Type 410. Their mechanical properties are comparable, with yield strengths of 350 to 410 MPa as annealed. With cold working, strength levels in excess of 690 MPa can be achieved. The least corrosion resistant grade in this group provides significantly better corrosion resistance than Type 405.

Nitrogen-strengthened alloys are austenitic stainless steels with nitrogen added for improved strength and corrosion resistance. Manganese is substituted for at least some nickel in these alloys to provide an austenitic structure at all temperatures. Typical applications could be weld studs, self-tapping screws, industrial screens, springs, wire products, antennas, cables, pole-line hardware, pump shafts and worm screws.

Higher up the scale, three grades (Carpenter's Gall-Tough, 15-15LC and 21Cr-6Ni-9Mn) provide corrosion resistance similar to that of Type 304 in various environments and twice the yield strength. They can generally withstand attack from many industrial chemicals and solvents, also resisting pitting caused by chlorides. In addition, they exhibit good ductility and excellent high temperature strength.

For greater strength at a good level of corrosion resistance, AISI Type 431 could fit the requirements. This is a magnetic martensitic, thermally hardenable stainless steel. Its combined corrosion resistance, hardness and toughness qualify it for aircraft fasteners and fittings.

The strongest alloy at this level of corrosion resistance is probably Carpenter Custom 455. It is a precipitation-hardening alloy offering good resistance to fresh water, industrial and marine atmospheres. In addition, it provides good ductility and notch toughness. Thus the alloy combines high strength, good corrosion resistance, simple heat treatment, and ease of fabrication. Applications include springs made from wire and strip, nuclear-reactor parts, high-performance fasteners and pumps and high-pressure components for vessels in contact with corrosive elements.

In selecting stainless steels, the method of fabricating the raw material into the finished product must be considered. In addition to the material's ability to be machined, cold formed, welded, and heat treated, the effects of fabrication processes on properties must be known. It may be necessary to modify fabrication procedures to correct, or prevent, possible degradation of properties. Therefore, after an alloy is selected on the basis of corrosion resistance and mechanical properties, it may be advisable to improve fabrication characteristics by using a modification of the chosen alloy. Many variations and modifications of the 16 basic stainless steels offer improved fabrication characteristics. Unfortunately, many modifications which improve one fabrication quality may cause another quality to decrease. In addition certain mechanical properties may be sacrificed; modifications to boost machinability may reduce the ability to be cold worked.

Quick guide to stainless steel selection

1. Select the level of corrosion resistance required for the application.
2. Select the level of strength.
3. For special fabrication problems, select one of the basic alloy modifications that provides the best fabrication characteristics.
4. Do a thorough value analysis to include the initial alloy price, the installed cost, and the effective life expectancy of the finished product.
5. Determine the availability of the raw material from the steel mill, service centre, warehouse or supplier, to arrive at the most economical and practical choice.

(Extracted from *Advanced Materials & Processes 4/94*)

Selecting coppers and copper alloys

Copper casting alloys are primarily selected for either their corrosion resistance, or their combination of corrosion resistance and mechanical properties. The materials also feature good castability, high machinability, and compared with other corrosion-resistant alloys, reasonable cost. Additional benefits include bio-fouling resistance—important in marine applications—and a spectrum of attractive colours. Many of the alloys also have favourable tribological properties which explains their widespread use for sleeve bearings, wear plates, gears, and other wear-prone components.

Cast coppers are high-purity metals containing at least 99.3 per cent Cu. (Wrought coppers have a slightly higher minimum copper content). Trace amounts of silver or phosphorus may be present. Silver imparts annealing resistance, while phosphorus facilitates welding. Neither element affects electrical conductivity significantly when present in such small concentrations. Electrical conductivity can be as high as 100 per cent IACS, while thermal conductivity can reach 391 W/m.K. Coppers have very modest strength and cannot be hardened by heat treatment.

Oxygen-free copper has the highest electrical and thermal conductivity among the cast copper alloys, but is essentially identical to phosphorus-deoxidized copper in other respects. Both types of coppers are readily weldable.

Whilst copper alloys are among the most easily cast engineering materials, unalloyed copper presents a number of casting difficulties: coarse, often columnar grain structures; rough surfaces; and a tendency to form shrinkage cavities. These problems can be overcome by foundry practice, the use of cast pure copper is generally reserved for applications demanding the highest electrical and/or thermal conductivities. Such products include large electrical connectors, and water-cooled, hot-metal handling equipment, such as blast furnace tuyeres.

Compared to pure copper, the dilute alloys have significantly higher strength, higher hardness and wear resistance, higher fatigue resistance and better castability, yet retain most of copper's electrical and thermal conductivity. Corrosion and oxidation resistance of these alloys are as good, or better, than those of pure copper, because alloying improves the chemical and mechanical properties of their protective oxide films. Within their temperature range, depending on the composition, no other engineering material can match their combination of conductivity, strength and corrosion resistance.

Several of the high-copper alloys can be age hardened. In the fully aged condition, the strength of chromium copper is roughly twice that of pure copper, and its electrical conductivity remains higher than 80 per cent IACS. Chromium copper is used for electromechanical products such as welding-machine clamps, resistance welding electrodes, and high-strength electrical cable connectors.

Age-hardening beryllium coppers can be further categorized as high-conductivity alloys and high-strength grades. Alloy selection depends on whether electrical or mechanical properties are more important. In the fully-aged condition, the high-conductivity alloy develops about 60 per cent of the strength, but twice the conductivity of the high-strength alloy.

Beryllium coppers are relatively expensive, but they can be very cost-effective when properly used, such as in plastic injection moulds. These casting alloys have high fluidity and can reproduce fine details in master patterns.

Brasses are the most commonly cast copper alloys, whereby zinc is the dominant alloying addition. They exhibit excellent castability, relatively low cost, together with a favourable combination of strength and corrosion resistance. Five sub-categories exist: red and leaded red, semi-red and leaded semi-red, yellow and leaded yellow, high-strength and leaded high-strength yellow (manganese bronzes), and silicon brasses/silicon bronzes.

Red brasses are alloys of copper, zinc, tin, and in some cases, lead. These alloys are of moderate strength with medium conductivity together with high aqueous and atmospheric corrosion resistance.

Semi-red brasses have a higher zinc content, which reduces corrosion resistance but has little effect on strength. The microstructure remains mostly single-phase alpha, although some body-centred cubic beta phase may appear as a result of coring.

Yellow and leaded yellow brasses have varying zinc contents. These alloys have microstructures ranging from essentially all-alpha, to ones with substantial amounts of the hard beta phase. Properties vary accordingly since beta is a potent strengthener. Beta slightly impairs room-temperature ductility, but also markedly improves ductility at temperatures approaching the solidus. Their corrosion resistance and cost are slightly lower than semi-red brasses.

High-strength brasses are also known as manganese bronzes and high-tensile brasses and are among the strongest as-cast copper-base materials. The mechanical properties of these brasses mainly derive from a high beta-phase content. Additional strength is provided by iron, a grain refiner that appears as precipitates of an iron-rich intermetallic compound. Manganese also contributes to strength, but its principal function deals with castability.

Silicon brasses/bronzes have foundry characteristics which include favourably low melting points and high fluidity. They are amenable to most casting methods and exhibit moderate strength and very good aqueous and atmospheric corrosion resistance. They are, however, susceptible to stress-corrosion cracking in severe environments.

Tin is a potent solid-solution strengthener in copper. It also increases corrosion resistance, as illustrated by the Bronze Age relics still found today. Binary Cu-Sn alloys retain the alpha solid solution up to 15.8 per cent Sn at 520° C, and whilst tins' solubility is much lower at room temperature, low-temperature transformations are very slow and can be ignored. Tin broadens the freezing range far more than zinc does, tin bronzes therefore tend to undergo a mushy stage during solidification which must be borne in mind when designing castings. Tin bronzes are stronger and more ductile than red and semi-red brases and are usable at higher temperatures than leaded alloys. They exhibit high wear resistance and low friction coefficient against steel.

The function of lead in Cu-Sn and Cu-Sn-Zn alloys are primarily to improve machinability and pressure tightness. Most copper alloys can produce pressure-tight castings with proper foundry practice, but extended-freezing-range alloys, such as the high-tin bronzes often require some lead to seal interconnected microporosity. Lead reduces tensile strength and ductility; however, the amount added can be balanced with regard to machinability and strength requirements.

Nickel-tin bronze alloys combine strength and toughness with good bearing properties and high corrosion resistance. They are amenable to most foundry processes, including permanent mould and investment/precision castings. These alloys are soft and ductile in the as-cast or solution-annealed and quenched condition, but the low temperature aging causes a spinodal decomposition that sharply raises mechanical properties.

Aluminium bronzes are best known for their combination of exceptional corrosion resistance; high mechanical strength, toughness, and wear resistance; and good casting and welding characteristics. They comprise a large family of alloys ranging from ductile, moderate-strength grades to some of the strongest copper-base compositions available. The corrosion resistance of aluminium bronzes is generally very high, especially in sea water, chlorides, and dilute acids, including sulphuric, phosphoric, hydrochloric and hydrofluoric. They are much less susceptible to crevice corrosion than stainless steels, and resist both pitting and stress-corrosion cracking.

Aluminium bronzes have replaced other copper-base alloys in a number of applications. In many cases they have proven to be technically viable and cost-effective alternatives to stainless steels.

Copper nickels, also called cupronickels, are solid-solution alloys to which iron, chromium, niobium and/or manganese are added for improved strength and corrosion resistance, particularly under conditions of high-velocity liquid flow. They have a notable corrosion-resistance in sea water and for virtual immunity to stress-corrosion cracking. Since the nickel content strongly affects alloy price, the use of these alloys needs to be justified by the severity of service conditions and the required product life. They are typically used aboard ships, on offshore platforms and in coastal power plants. They are considered to be the best materials for evaporative desalination plants.

Nickel silvers have low to moderate strength, depending on their grade. They exhibit high fluidity during casting and can reproduce fine details. Tin and nickel impart good aqueous corrosion resistance, while lead provides pressure tightness and machinability.

One of the most significant recent trends in the copper-base foundry industry is an increased emphasis on casting methods that provide high-precision products with near-net shapes and fine surface finishes. New, innovative processes are finding niche markets, whilst substantial growth is being experienced by already accepted methods. The most active area of copper alloy development is currently the plumbing goods industry where a mandate to reduce even trace levels of lead from drinking water has prompted a search for alternatives to traditional copper-base alloys. (Extracted from *Advanced Materials & Processes 6/94*)

Material wealth — copper's versatility

Copper and copper alloys are cost-effective for a variety of reasons. They are strong, corrosion resistant, readily fabricated and easily machined. Near-to-net shape preforms can easily be produced keeping overall production costs low. Compositions and properties of copper and copper alloys can be varied to suit many requirements. Components made from them are reliable and need little special finishing, giving long life-times and minimizing the need for costly replacement and repair. They are also usually recyclable, ensuring value even at the end of the component life. Copper alloys are suitable for a very wide range of applications from tiny precision electrical contacts capable of withstanding millions of make break cycles to huge canisters for storing nuclear waste in complete safety; from close-tolerance instrument parts to massive tough bearings and propellers.

More than half the copper produced in the world is used by the electrical industries the vast majority in the form of very pure, high conductivity copper. This can be wrought or cast and is readily available in a wide range of shapes and sizes.

The most commonly available copper is known as "electrolytic tough-pitch copper" ("electro"). This contains approximately 0.03 per cent oxygen which improves ductility and conductivity. If the copper is required to be welded or brazed it is necessary to use "phosphorus deoxidized copper". This is commonly used for applications such as calorifiers and water service tubing but is readily available in all wrought forms.

Oxygen-free coppers are made by melting and casting the copper in a controlled atmosphere to give a very low residual oxygen content. These materials should be specified where resistance to embrittlement is required with no loss in conductivity. An electronic grade of oxygen-free copper which has a particularly low content of volatile impurities and forms excellent glass-to-metal seals is specified for applications in which the copper is to be used in high-vacuum.

For applications where good conductivity is required with increased strength, one of the low alloyed coppers can be specified. These generally contain a total alloy addition of less than 2 per cent. The most important of these are copper-silver, copper chromium, copper-nickel-silicon, copper-beryllium and the free-machining alloys, copper-sulphur and copper-tellurium.

All copper alloys can be recycled and in fact 40 per cent of the copper consumed world-wide comes from recycled metal. Uncontaminated high conductivity copper scrap can be refined to meet the exacting specification of Grade "A" cathode, the material required for drawing to ultra-fine wire. Slightly less pure material can be used for non-electrical purposes although the impurity limits must still be very tightly controlled. Copper alloy scrap and copper scrap that contain other metals such as tin from soldering operations can be used to produce copper alloys. For example, gunmetals require the addition of both lead and tin.

The brass industry is almost entirely dependent on recycling. Brass for extrusion and hot stamping is normally made from a basic melt of carefully selected scrap, the final composition being adjusted before pouring by the addition of virgin copper or zinc as required. Brass for rolling or wire drawing must meet tighter limits for impurity content, so frequently a larger proportion of virgin metal is needed. (Extracted from *Engineering, October 1994*)

2. ALLOYS FOR HIGH-TEMPERATURE APPLICATIONS

Trends in high-temperature alloys

The selection of cost-effective alloys for high-temperature service depends on knowledge of service requirements and materials capability. Each temperature regime offers several alloy options, depending on mechanical property and corrosion-resistance requirements.

Modern high-temperature alloys have undergone little change in chemical composition in the past 30 years. Most possible combinations of iron, nickel, cobalt, chromium, molybdenum, tungsten, titanium, aluminium, niobium and trace elements have been evaluated, leaving little room for further opportunities. Therefore, recent improvements in alloy performance have been primarily achieved through processing enhancements.

High-temperature alloys broadly refer to materials that provide strength, environmental resistance and stability within the 260° to 1200° C temperature range. They have generally been used in the presence of combustion from heat sources such as turbine engines, power plants, furnaces and pollution control equipment. In order to retain strength under these conditions, it is imperative that their microstructures remain stable at high operating temperatures.

This stability requirement represents a constant challenge to designers. To achieve beneficial properties, metals are usually heat-treated to a metastable condition. However, this reverts to a less useful equilibrium structure upon elevated-temperature exposure. It is therefore critical that designers understand and document expected operating conditions. Particular consideration must be given to aggressive environments, which compound the effects of elevated temperatures.

From a competitive standpoint, alloy selection must be based on expected cost-effectiveness. The best choice is usually the lowest-cost material able to meet design criteria. However, a higher-cost material offering greater reliability may be justified for certain components in a system that is critical and or expensive to shut down for maintenance. A knowledge of alloy capabilities can be useful in making this decision.

High-temperature alloys can be divided into four groups, based on matrix composition.

- **Iron-base alloys**: This group comprises the low chromium alloys such as 3Cr-1Mo-V, 4340 alloy, Carpenter's AerMet 100 alloy and Maraging 250, as well as the 12 per cent chromium, martensitic stainless steels such as 636 alloy, Greek Ascoloy (AMS 5616) H-46, Moly Ascoloy and Lapelloy "C".

Alloys in the latter group are sometimes designated Super 12 Chrome steels, and they contain refractory elements such as molybdenum and tungsten for greater strength at elevated temperatures. Other elements are also added in small amounts for strengthening purposes. These iron-base alloys can be used at temperatures up to 400° C, whilst the 12 per cent chromium martensitics may be used at temperatures up to 650° C, whereby only moderate strength is provided above 540° C.

- **Iron-nickel base Alloys**: Both non-age-hardenable and age-hardenable grades are included in this category. Type 330 stainless and N-155 are examples of solid solution-strengthened (non-age-hardenable) alloys.

Age-hardenable grades include Carpenter's Pyromet alloys A-286, 901, V-57, 706, CTX-1, CTX-9 and Thermo-Span alloy. All contain niobium and or titanium, as well as aluminium to promote age-hardening. Good strength and hardness are achieved in the 600° to 700° C temperature range when the alloys are solution treated and aged.

- **Nickel-base alloys**: These alloys contain more nickel than iron, where nickel ranges between 50 and 80 per cent. Other alloying elements include molybdenum, tungsten, aluminium, titanium, niobium, cobalt and boron. This group includes both age-hardenable and non-age-hardenable grades.

- **Cobalt-base alloys**: Typical for this category is L-605, which contains 50 per cent cobalt in addition to nickel, iron, chromium and tungsten. It is a ductile alloy suitable for service up to about 1040° C. Metals in this group are particularly useful in sulphur-bearing environments where nickel-based alloys are readily attacked.

As temperature and strength requirements increase, so does the necessary alloy content. Iron-base martensitic alloys are most commonly used in the 260° to 540° C temperature range. Above this temperature, the martensitic alloys tend to over-temper to an unacceptably low strength for many applications. However, these alloys are economical due to their high iron content, generally being the most cost-effective in this temperature range. Higher strength can be provided by ultra-high-strength materials such as maraging steels, but these grades are not recommended for use above 400° C.

Precipitation-hardened alloys dominate high-strength applications in the 540° to 815° C temperature range. These alloy systems consist of an austenitic matrix strengthened by precipitates of nickel and aluminium, titanium, or niobium, and solid solution-strengthening elements such as molybdenum.

The temperature limit for these alloys is reached when the precipitates start to over-age and dissolve. Heat resistance can be improved, however, by increasing precipitate-forming elements. Nickel must also be continually increased to form the intermetallic precipitates and to stabilize the austenitic structure, given the higher alloy content. Cobalt may also be added to reduce the solubility of precipitates. Refractory elements tungsten and molybdenum can be added to increase high-temperature stiffness. However, all these additions to improve the temperature capability also add significantly to the cost.

Alloy selection depends on mechanical property requirements such as strength, creep and fatigue, as well as the maximum exposure temperature. The alloy A-286 occupies the "low end" of the austenitic precipitation-hardening high-temperature alloys. It has moderate strength and long-term service capability up to 620° C. With its nominal 25 per cent nickel content, it can be quite cost-effective. The alloy Pyromet 718, perhaps the most universal high-temperature alloy, accounts for the largest percentage of total industry superalloy production. It possesses high strength and creep resistance up to 675° C and a reasonable level of both properties up to 760° C. It has excellent fatigue properties. Large-scale production makes this alloy more economical than the composition would usually suggest.

When temperatures exceed 675° C and superior creep properties up to 760° C are needed, the alloy Waspaloy is probably the most suitable. However, its higher nickel and cobalt contents mean a higher cost. The alloy Rene 41 offers service capabilities beyond Waspaloy due to its higher titanium, aluminium and molybdenum contents. It has higher strength and creep resistance than Waspaloy, but slightly less fatigue resistance. Alloy 720 serves in the same temperature range, but provides superior strength and creep resistance. With its high alloy content, it is at the practical upper limit for conventionally cast and wrought alloys and is therefore more costly and difficult to produce.

Controlled thermal-expansion alloys are an important family within the precipitation-hardening group. These are special-purpose materials providing low coefficients of thermal expansion within their intended service temperature ranges: -40° to 680° C. Typical alloys in this group are Pyromet CTX-1, CTX-3, CTX-909 and Thermo-Span. These alloys rely on a chromium-free or low-chromium, nickel-iron-cobalt matrix, which is austenitic yet ferromagnetic, and provides low expansion characteristics. They are prone to oxidation above 540° C, but at the same time provide unique capabilities in sealing and thermal fatigue-limited applications.

The precipitation strengthening mechanism is relatively ineffective above 870° C, as the precipitates over-age and become unstable, causing a loss of integrity. Therefore, solid solution-strengthened alloys dominate in the upper temperature range.

Solid solution-strengthening consists of alloying a matrix with elements having large atomic diameters, such as molybdenum and tungsten in a nickel-chromium or nickel-cobalt-chromium matrix. The large atoms stiffen the material, providing creep resistance; however, these materials cannot be strengthened to the levels of precipitation-hardening alloys.

The lowest-cost materials suitable for temperatures above 870° C are the 300 series stainless steels. While they provide only low levels of strength, some grades possess sufficient environmental resistance for continuous service as high as 1150° C. The three best choices, in increasing order of capability are: Types 309, 310, and 330 stainless steels. Exposure of 309 and 310 at 870° C causes sigma-phase embrittlement, making 330 the most forgiving of the stainless steels. Higher strength capabilities can be found in more highly alloyed solid solution-strengthened metals such as Pyromet 600, 601, L605, 680 and 625, and alloys S and 188. Exotic oxide-dispersion-strengthened metals can be considered for even more severe service conditions

The scarcity of new heat-resisting alloys has not inhibited the drive for improved materials and component performance. Alloy users have benefited from producers' improved quality control, cost containment, better homogeneity, tighter inspection limits, greater cleanliness, enhanced workability, and improved reliability. Larger-diameter products have become increasingly available.

Producers are continually evaluating methods of manufacture, looking for ways to reduce alloy variation, improve yields, reduce cycle times, and enhance materials characteristics. Process control has been particularly effective in reducing product variation. Instead of working to specification minimums, some alloy producers, and users, now prefer to establish and work to upper and lower control limits, often exceeding the minimum requirements. This approach has allowed component designers to design to much higher stress levels while still allowing margins of safety. (Extracted from *Advanced Materials & Processes, 10/95*)

The next generation of aluminium-lithium alloys

The advantages of aluminium-lithium (Al-Li) alloys has been well-documented in the past, but their impact on the aerospace market has fallen short of initial expectations. Part of the reason is the lower ductility, toughness and stress-corrosion resistance of Al-Li alloys compared with conventional aerospace-quality aluminium alloys. In addition, they lose toughness during either long-term exposure at room temperature, or short-term exposure at slightly elevated temperatures. This latter problem could prevent these alloys from being considered for supersonic aircraft, where the high airframe temperature accelerates embrittlement.

A vacuum refining process has been developed by Comalco Aluminium Ltd. (Melbourne, Australia), that provides improved mechanical properties. The patented technology also allows higher levels of lithium, which results in higher stiffness and lower densities. For example, alloys with 3.3 per cent lithium and very low amounts of hydrogen and alkali metal impurities demonstrate good mechanical properties. They also exhibit good weldability, as demonstrated in "varestraint" testing, which evaluates the tendency to crack during welding.

The high purity of these VacLite alloys ensures that grain boundary fracture is minimized, and cleavage fracture is reduced almost to the limit of detectability. Furthermore, advanced vacuum techniques using electron beam melting, may eventually reduce impurities to a level at which fracture occurs only in a ductile, transgranular manner.

Investigations were undertaken to determine the rate at which toughness was lost. It showed that the mechanisms are obviously temperature-dependent. At 20° C, the alloys lose substantial toughness only after years of exposure, while the same degree of embrittlement can occur in two days in the 120° to 150° C temperature range. It then became necessary to find the mechanism responsible for this embrittlement. The most widely accepted was strain localization, which occurs as a result of the ordered structure of the hardening precipitates. It enables dislocations to stay on one slip plane. As a result, dislocations pile up, and can cause cracking at obstacles such as grain boundaries.

Another possible mechanism is liquid metal embrittlement, caused by alkali-metal impurities, including sodium, potassium, caesium, and rubidium. When these are present in large amounts, they have been found to reduce toughness. They are introduced into the aluminium mainly by lithium, which may typically contain 100 to 200 ppm $Na+K$. In addition, these impurities can be introduced by refractories in the melting and casting facility, and in the aluminium pig.

For a long time the aluminium industry made no attempt to reduce these impurities below those found in commercially pure (CP) Al-Li alloys. One reason was the belief that the levels were already so low that further purification would have no effect on toughness. The loss of toughness was considered to be caused by very thin grain boundary layers of solid sodium. Other impurities were rarely discussed, partly because values for potassium, caesium, and rubidium could not be reliably measured before the advent of glow discharge mass spectrometry (GDMS). A simple test carried out in the 1970s to determine the validity of liquid metal embrittlement would be to measure the toughness of an impure alloy over a range of temperatures above and below room temperature. If this embrittlement was a factor, the toughness should increase down to -78° C, where all liquid would solidify at the ternary eutectic. The results of this experiment on an equiaxed recrystallized alloy not only validated the mechanism, but also demonstrated the dramatic increase in toughness of Al-Li alloys at low temperatures.

More recently it has been suggested that the increase in toughness below room temperature could be caused by an increase in the amount of delamination. These occur in CP Al-Li alloys because of the pancake shape of the usually unrecrystallized grains. However, this suggestion overlooks the fact than an increase in toughness below room temperature is shown by both the equiaxed recrystallized alloys, and coarse-grained investment casting alloys, even though they do not show delaminations.

Imaging secondary ion mass spectrometry is probably the best technique for showing the distribution and concentrations of alkali metal impurities and hydrogen in Al-Li alloys. Many experiments have been undertaken to prove this theory.

Tests in the past have strongly suggested that alkali-metal impurities above the levels found in commercial Al-Li alloys can result in embrittlement. Until the vacuum-refining technique designed by Comalco was operational, it was difficult to find an answer as to how reducing the level to below that found in commercial alloys improved toughness, and how could they be removed. The refining technique depends on the fact that all these impurities have much higher vapour pressures than aluminium and lithium, so that under optimum refining conditions, the total impurity content can be reduced to less than 1ppm. The same process reduces the hydrogen content, which is always higher in Al-Li alloys than in conventional alloys because lithium increases the solubility of hydrogen in aluminium. A distinction should be made between vacuum melting and vacuum refining.

As previously mentioned, commercial purity Al-Li alloys lose toughness after long-term exposure at room temperature, and much shorter exposures at higher temperatures. This delayed embrittlement might seem surprising in view of the fact that the alloys are initially aged to peak, or near-peak, strength, and might be expected to be stable below the ageing temperature. Some of the loss of toughness could be caused by a small increase in yield strength during additional ageing, which can occur even at room temperature. However, even in the most favourable cases where the strength-toughness relationship remains unchanged after exposure, there would be a weight penalty in structures where fracture toughness is one of the design parameters Further experiments showed, however, that delayed embrittlement may not be directly related to a simple increase in strength. Tests found embrittlement of alloy 8090 plate after exposure at 150° C, with no increase in yield strength. It was also found that a loss of toughness in 2090 plate during ageing at 160° C, and a loss of toughness of 8090 plate during ageing at 260° C, even though the yield strength of both alloys was decreased by the exposure. High-purity 2090 does not show the substantial loss of toughness after exposure that is seen in commercially pure materials.

This greater loss of toughness in 2090 plate, compared with sheet, may be caused by its higher lithium content, which in a commercially produced alloy would result in both a higher alkali-metal impurity content and a much higher hydrogen content.

Further questions have been raised on where more work needs to be carried out, i.e., can hydrogen alone act to embrittle during long exposures below the ageing temperature, or does it need to be contained in a grain boundary reservoir? What other mechanisms are acting during long-term exposures to temperatures above the 65° C already investigated? Can the redistribution or continued precipitation of alkali-metal impurities at these temperatures cause embrittlement directly, regardless of the hydrogen content?

Today, the superior physical properties of Al-Li alloys can be combined with the improved mechanical properties achieved through vacuum refining. The upper limit for lithium content in alloys made by vacuum refining is determined, not by mechanical properties, but by the loss of corrosion resistance that results when the amount of lithium exceeds the solid solubility limit, and primary Al-Li particles are formed.

The following properties are improved by vacuum refining: toughness; stress-corrosion cracking resistance; weldability (the tendency to crack during welding is reduced by the higher purity); cold drawing (greater cold reduction without cracking); and creep cracking resistance (related to the alkali-metal impurity level).

Many complicated interactions take place between the alkali-metal impurity particles, their associated dissolved hydrogen atoms, the microstructure and the available fracture mechanisms.

In Al-Li alloys containing many large brittle particles, such as the investment-cast Al-2.6 Li-3 Si alloy, stress concentrations develop within the grains. When they combine with their liquid metal envelopes, these stress concentrations enable cleavage to be the predominant fracture mechanism. However, particles harder and stiffer than the aluminium matrix will favour a breakdown of the particle matrix interface, and cause cracks to grow along the stress axis for tensile stresses, but at right angles to the stress axis for compressive stresses. Liquid-metal particles in a solid matrix cause cracks to grow at right angles to the stress axis for tensile stresses, but perpendicular to the stress axis for compressive stresses. Hard particles in a liquid-metal envelope provide both stress concentrations for initiating fracture, and a low-energy fracture mechanism for propagating the cracks. Because of the relative ease of cleavage by the above mechanism in commercially pure Al-Li alloys, inclusions are considerably more detrimental to mechanical properties than they would be in conventional aluminium alloys. As the hard-particle size and volume fraction are reduced, the probability of cleavage nucleation is also reduced. In addition, reducing the alkali-metal impurity level improves toughness by reducing the extent to which cleavage cracks can grow. Since both residual alkali-metal impurities and hydrogen introduced by cathodic charging can reduce the toughness and ductility of Al-Li alloys, it is not surprising that the combination of these impurities is more detrimental than either acting alone. Both hydrogen and alkali-metal impurities behave in a similar manner during heat treatment. (Extracted from *Advanced Materials & Processes, 5 94*)

Bolting alloy for high temperatures

SPS Technologies (Jenkintown, PA, USA) have developed a high-strength, high-temperature fastener alloy to meet the requirements of today's advanced turbine engines. Designated Aerex 350, it is based on the multiphase materials cobalt, nickel and molybdenum, to take advantage of their low notch sensitivity, high strength and excellent resistance to creep and corrosion. Researchers sought to produce physical properties equivalent to those of conventional nickel-base superalloys, such as Waspaloy. Resulting from this, thermal expansion coefficient, thermal conductivity, electrical resistivity, specific heat, enthalpy, modulus, Poisson's ratio and density are all in ranges common to that class.

Aerex 350 Alloy provides a strength of 1210 MPa above 650° C, as well as an excellent combination of mechanical properties across a wide temperature range. Its strength is imparted by a combination of cold working and age hardening. Deformation promotes a martensitic transformation in which thin platelets of hexagonal close packed phase form on the {111} planes of the face-centred cubic matrix. These platelets hinder the motion of dislocations and lead to significant strengthening.

Ageing causes the precipitation of gamma prime, which is the ordered face-centred-cubic phase responsible for the high strength of MP 159 and many nickel-base superalloys. The size, stability, and lattice mismatch of gamma prime in Aerex 350 Alloy have been optimized by a careful selection of heat treatment cycles and hardening elements. The result is creep and stress-rupture resistance that are superior to any other fastener alloy in the 620° to 760° C temperature range.

The thermal-mechanical processing of this alloy is designed to maximize its high-temperature performance. Because coarse-grain materials are generally stronger at elevated temperatures than those with fine grains, processing is designed to produce relatively coarse grains.

Aerex 350 Alloy was developed specifically for fasteners, as opposed to many other high-temperature fastener alloys which were originally developed for turbine blades or disks. As a result, it displays a superior combination of notched tensile strength, impact strength, creep resistance, thermal stability, and stress relaxation resistance.

Tensile properties show a favourable combination of strength and ductility over the use-temperature range, displaying little change after exposure to elevated temperatures. Further, tensile tests show a consistent yield/tensile-strength ratio over the entire test temperature range, indicating the absence of a ductility trough or embrittlement that might cause service problems. Notch ductility is also excellent; fastener strength exceeds material strength, whereas many superalloys tend to exhibit the opposite behaviour.

The cryogenic impact strength of this alloy is higher than the room temperature impact strength of other alloys in its strength class, indicating high toughness. The shear strength/ultimate tensile strength ratio averages 0.62, significantly higher than the 0.55 value exhibited by most cold-reduced and aged fastener alloys. In addition, Aerex 350 Alloy is readily forgeable, unlike some P/M turbine disk alloys which have been used for fastener applications, showing that even the most complex configurations can be manufactured using conventional equipment. (Extracted from *Advanced Materials & Processes*, 2/95)

Cobalt-base alloys

Cobalt alloys possess very high strengths at elevated temperatures, and exhibit outstanding resistance to galling and various forms of erosion. Critical valves in the chemical processing, oil and gas, and power industries depend on them for long-term, trouble-free operation, and they enhance the performance of jet engine combustors.

The cobalt-based alloys in use today are based on the work done by Elwood Haynes at the beginning of the century. He discovered the benefits of adding chromium to cobalt, and patented the ternary Co-Cr-W and Co-Cr-Mo alloys, from which modern compositions have evolved. He noted that chromium was found to enhance resistance to aqueous corrosion and oxidation and that in cobalt, chromium also had a remarkable effect upon strength, both at room and elevated temperatures. This strength is further enhanced by adding tungsten and molybdenum.

In theory, cobalt and most of its alloys exhibit two atomic forms, face-centred cubic (FCC) and close-packed hexagonal (CPH). In practice, the CPH form is difficult to generate during cooling, and most cobalt-based alloys exhibit a metastable FCC structure at low temperatures.

However, the transformation to CPH is easily triggered by mechanical stress during plastic deformation. The transformation tendency depends on the transformation temperature, which in turn is influenced by the levels of various alloying additions. Nickel, iron, manganese, and carbon are FCC stabilizers and reduce the transformation temperature; chromium, molybdenum, silicon and tungsten are CPH stabilizers and have the opposite effect.

Cobalt-base alloys are extremely resistant to many forms of wear, are strong over a wide temperature range, and are moderately resistant to many forms of corrosion. Individual compositions are typically tailored to meet specific industrial demands. For example, alloys optimized for wear resistance generally include significant carbon additions, which result in the formation of carbides in the microstructure during alloy solidification. These carbides increase the hardness of the alloys and their resistance to low-stress abrasion, at the expense of some ductility and corrosion resistance.

Alloys which are designed for service in severely corrosive environments typically contain low carbon levels. This markedly improves resistance to corrosion, but also increases ductility, allowing these alloys to be easily forged and rolled into wrought products. They are also resistant to several forms of wear, in spite of their lower hardness value.

Low-carbon, cobalt-based alloys are characterized by high resistance to both aqueous and hot corrosion, good ductility, high strength, and ease of wrought processing. Some are also very resistant to wear other than low-stress abrasion, for which a high-volume fraction of carbides is desirable.

Cobalt-based alloys exhibit passive behaviour in oxidizing environments such as nitric acid. Those with a significant molybdenum content also resist mild reducing environments such as dilute sulphuric and hydrochloric acids. These alloys also possess moderate resistance to stress-corrosion cracking. For example, four-point bend tests in magnesium chloride show that R31233 exceeds the performance of N08020, a high-nickel stainless steel. R31233 also resists sulphide stress cracking in sour gas environments at elevated temperatures.

The low-carbon alloys are relatively strong at temperatures in excess of 500° C, and possess good to excellent resistance to oxidation and sulphidation. They further exhibit exceptional resistance to certain forms of erosion, abrasion and sliding wear. Their resistance to low-stress abrasion is limited by the absence of large carbide particles in the microstructure. However, under high-stress abrasive conditions at high temperatures, both low- and high-carbon alloys excel as a result of their higher strengths.

The levels of damage encountered under self-coupled sliding conditions have been recorded using a modification of the ASTM G98 test procedure. They show that in dry, sliding systems, the use of at least one cobalt alloy surface is often extremely beneficial.

The main benefits of a high carbon content are increased hardness and enhanced resistance to low-stress abrasion, both of which increase with increasing carbon content. Test results of two-layer weld overlays do not take into account the differences in matrix composition between the alloys, but they do indicate the strong influence of carbon content, hence carbide volume fraction. Under high-stress abrasion conditions, the carbon content is less influential.

In forming carbides, the carbon ties up a portion of vital alloying elements such as chromium. The effective chromium content from a corrosion standpoint (the chromium remaining in the solid solution) is therefore considerably lower than indicated by the nominal composition. This situation is aggravated by the fact that most of the high-carbon alloys are not amenable to wrought processing, and therefore must be used in the form of castings or weld overlays, which are inherently less homogeneous from a compositional standpoint. The carbides also result in low ductilities. This should be taken into account both when applying weld overlays, and when considering alloys for components that will see high-impact service.

Cobalt-based alloys are used extensively in gas turbines, power generation, oil and gas equipment, chemical processing, marine components, and steel production. For gas-turbine applications, high strength and oxidation resistance are the primary requirements. Alloys R30188 and R30605 have been designed with these requirements in mind, and both have been successfully used for fabricated components in the hot sections of aircraft gas turbines. Further applications have included transition ducts, combustor cans, spray bars, flameholders and afterburners.

In the power industry, the low- and medium-carbon alloys have been widely used for steam-valve seating surfaces. The key attributes here include resistance to galling and resistance to steam erosion. Their resistance to high-speed water-droplet erosion makes them suitable for applications such as erosion shields on low-pressure steam turbine blades.

In the oil and gas industry, alloy R30006 prevents galling when used as an overlay on well head gate valves. Alloy 190 protects the bearing surfaces of rotary drill bits from damage caused by high stresses and abrasive particles generated by the drilling process.

Major applications in the chemical processing industries include valves, pumps, mixers and nozzles. Alloy R31233 is widely specified for severe environments, such as liner material for large paint-pigment mixers subject to slurry erosion and corrosion.

In the marine field, the cobalt-based alloys are used for power plant valves, and for coating the sliding surfaces of large rudder and stabilizer bearings. These bearings must withstand high stresses, are exposed to seawater, and are in locations where lubrication is impractical. These are typically coated with alloy 306, using the submerged-arc welding process.

Applications in steel production exploit cobalt's great strength and resistance to high-stress abrasion at high temperatures. Typical applications include hot-shear blades, guide rolls, ingot tong bits, and coke-oven pusher shoes. (Extracted from *Advanced Materials and Processes, 4/94*)

Fatigue life of titanium alloys

The mechanical properties associated with a given microstructure of titanium alloys can be superior in some respects, while inferior in others, or they may represent a compromise. Since the surface of a mechanically loaded part often experiences service conditions different than the bulk, it can make sense to tailor microstructural variations from the surface to the interior to meet the differing requirements, as is done in the carburizing of steels.

Cold working induced by mechanical surface treatments can be used to develop a surface microstructure different from that in the bulk, thus combining the optimum features of both, even in cases where conventional thermo-mechanical processing may not be practical, as in thick sections. A distinct advantage to be gained by altering the surface microstructure is that such alterations are more stable than those induced by mechanical surface treatments alone.

Mechanical surface treatments such as shot peening and surface rolling can be applied alone, or in combination with various heat treatments to develop optimum properties in mechanically loaded titanium parts. The particular treatment applied should reflect the type of alloy, to make use of its characteristic response to heat treatment and or thermo-mechanical processing.

For α alloys, a mechanical surface treatment and subsequent recrystallization offers the possibility of combining the high strengths and endurance limits associated with fine grains, and the superior long through-crack fatigue crack-growth behaviour and fracture toughness of coarse grains. To maximize the total fatigue life in thicker sections, fine grains are needed on the surface, where good resistance to crack initiation is critical. Coarse grains in the interior can reduce the driving force for long crack growth.

Because (α + β) and near-α alloys are often intended for high-temperature service (for example in gas turbines), creep resistance is an important consideration. In this regard, lamellar microstructures would be preferable. However, these microstructures have poor fatigue resistance, particularly in the low cycle fatigue (LCF) regime, where surface crack growth determines fatigue life. In such cases, a variation in phase morphology between the surface and the core can be beneficial.

For β alloys such as Ti-3Al-8V-6Cr-4Mo-4Zr, both shot peening and surface rolling have been combined with specially developed ageing treatments to selectively age-harden only the surface. This new thermo-mechanical surface treatment shows promise for improving properties of high-strength springs and fasteners. (Extracted from *Advanced Materials & Processes, 7/94*)

Nickel alloys combat high-temperature corrosion

During the last few decades, a better understanding of alloying effects, advances in melting technology, and the development of controlled thermo-mechanical processing have led to new and improved high-temperature alloys. Most such alloys have sufficient amounts of chromium (with or without additions of aluminium or silicon), to form chromium oxide, alumina and/or silica protective oxide scales, which provide resistance to environmental degradation. However, oxides cannot protect against failure by creep, mechanical or thermal fatigue, thermal shock, or embrittlement. Failure is typically caused by a combination of two or more attack modes, which synergistically accelerate degradation.

To counter these attacks, two new nickel-base alloys have been developed, in which high-temperature corrosion resistance has been optimized by the careful addition of elements such as chromium, aluminium, silicon and rare earths. They provide economical and reliable solutions to attack by oxygen, sulphur, halogens, carbon compounds and nitrogen in a range of high-temperature applications. Alloy 45TM has been successfully used in coal gasification equipment, incinerators, refineries and process machinery involving severe sulphidizing conditions. Alloy 602CA is utilized in heat-treating equipment, catalytic automotive parts, and chemical processing apparatus.

Alloy 602CA combines the beneficial effects of high levels of chromium, aluminium and carbon with micro-alloying amounts of titanium, zirconium and yttrium in a nickel matrix. The relatively high carbon content, approximately 0.2 per cent, in conjunction with 25 per cent chromium, ensures the precipitation of bulky, homogeneously distributed carbides having typical diameters of 5 to 10μm. Microalloying with titanium and zirconium further allows for finely distributed carbides and carbonitrides. Solution annealing, even at 1200° C, does not dissolve all these stable carbides. Therefore, the alloy maintains relatively high creep strength because of the combination of solid-solution hardening and carbide strengthening. The addition of approximately 2.1 per cent aluminium allows the formation of a continuous, homogeneous, self-repairing aluminium oxide sublayer beneath the chromium oxide layer, which synergistically imparts excellent resistance to oxidation as well as carburization. The addition of "reactive elements", such as yttrium, significantly increases the adhesion and spalling resistance of the oxide layers, thereby further enhancing its high-temperature corrosion resistance.

Alloy 45TM improves high-temperature corrosion resistance by a suitable balance of high chromium and high silicon in a nickel matrix. In addition, microalloying with rare earths assures the formation of adherent external chromium oxide layers and silica sublayers even at very low oxygen partial pressures. Synergism of the oxide layers results in high resistance to sulphidation and good resistance to carburization, chlorination and oxidation.

High-temperature degradation is typically caused by oxidation, carburization, sulphidation and/or halogenation. Each is caused by specific corrosive media and may be minimized by the addition of appropriate alloying elements as shown below.

- **Oxidation:** Elements having greater thermo-dynamic affinity for oxygen tend to form passive barriers in alloy systems, thus providing the required resistance. Chromium, aluminium and silicon are the three major elements that develop these passive barriers. However, the usefulness of a protective chromium oxide layer is limited to around 950° C. However, chromium oxide combined with aluminium oxide significantly enhances oxidation resistance at temperatures up to 1200° C. Both alloys show good resistance in cyclic oxidation tests because of the higher thermodynamic stability of aluminium oxide and the formation of sublayers of silica at very low partial pressures. The addition of rare earths further reduces cracking, fissuring and spalling of the protective oxide layers.

Cyclic oxidation testing of various iron-, nickel- and cobalt-base alloys for periods up to 1,200 hours showed that both 602CA and 45TM alloys provide superior performance. A metallographic examination of alloy 602CA shows the presence of a continuous alumina sublayer without any selective internal oxidation. However, alloy 601 is affected by selective internal oxidation, and it does not contain enough aluminium to form a continuous alumina sublayer. Higher thermodynamic stability and more than five orders of magnitude lower dissociation pressure of alumina are the primary reasons that continuous protective alumina layers are formed in alloy 602CA.

- **Carburization/metaldusting:** In addition to oxygen attack, high-temperature alloys are frequently subjected to attack by carbon compounds. The degradation of metallic systems in carburizing environments can take two forms: carburization and metal dusting. Because carbon has very low solubility in nickel, high nickel contents are beneficial for imparting carburization resistance. Alloys high in chromium, aluminium and silicon form protective oxide layers that prevent the ingress of carbonaceous corrosive species, thus providing improved resistance. However, if samples are exposed to alternating carburizing and oxidizing environments, their precipitated carbides are converted to oxides. Liberated carbon monoxide widens grain boundaries, loosening the oxide layer and initiating accelerated deterioration.

A study was undertaken on the relative influence of nickel and chromium on the carburization resistance of various alloys. This study confirmed the beneficial effects of nickel, but the role of chromium varied for different levels of nickel. Silicon was found to be very beneficial in improving carburization resistance. Small additions of elements such as titanium, niobium, tungsten and rare-earth elements have also been shown to improve carburization resistance.

- **Sulphidation:** Sulphidation involves the interaction of metal with sulphur to form sulphide scale. Since sulphur is one of the most common corrosive contaminants in high-temperature industrial environments, this mode of attack is frequently encountered. Sulphidation is influenced by both sulphur and oxygen activities, and formation of metal sulphides leads to severe damage. One example of this damage is the development of porous layers offering little protection. Because the volume of metal sulphides is 2.5 to 2.9 times greater than that of the corresponding metal oxides, the resulting stresses lead to severe flaking. Another reason they are so damaging is that metal sulphides have lower melting points than the corresponding oxides or carbides. As a result, corrosive attack is catastrophic because of the increase in the diffusion rate by several orders of magnitude via the liquid phase.

High-nickel alloys, such as 600/601, are particularly susceptible to sulphidation. However, resistance to sulphidation can generally be improved by increasing chromium levels. It can also be improved by the presence of cobalt, as cobalt-based alloys, as well as cobalt-containing alloys, provide a higher resistance to sulphidation attack. In addition, high cobalt levels in nickel-base alloys reduce the rate of diffusion of sulphur in the matrix, and reduce the risk of developing low-melting-point eutectics.

Silicon and aluminium reduce corrosion in oxidizing-sulphidizing media by quickly forming protective scales. Elements such as manganese, magnesium, calcium, cerium and yttrium increase resistance to sulphidation because they bind sulphur in a stable form, and thus prevent any further reaction, especially with nickel and chromium.

Laboratory testing in sulphidizing environments is very difficult because of the mode and unpredictability of breakaway corrosion. Furthermore, the corrosion rate may be linear or parabolic for hundreds or even a few thousand hours, and then suddenly may accelerate to rapid failure.

- **Halogenation:** Halogen and halogen compounds generally attack via the gaseous phase or molten salt compounds. Salts cause slagging and disintegration of the oxide layer; the gas-phase halogens penetrate deeply into the material without destroying the oxide layer. Therefore, pre-oxidation is of no benefit.

Diffused halides react to form heavy metal halides, which cause high rates of metal loss because of their low melting points and high vapour pressures. In contrast, nickel halides have low vapour pressure, enabling alloys high in nickel content to resist chlorination. Media containing fluorine are less aggressive than chlorine-containing media, and thus permit higher material service temperature. This is also confirmed by the higher melting points and lower vapour pressures of metal fluorides compared with corresponding metal chlorides. (Extracted from *Advanced Materials & Processes, 10 95*)

Commercial casting of nickel aluminide alloys

Commercial development of nickel alluminides has until recently been limited by a lack of the technological know-how for melting and casting these alloys. However, the Exo-Melt method, a patented process developed by United Defense LP (Anniston, AL, USA), has recently been used to successfully melt and pour commercial-sized heats of this new class of engineering materials.

Nickel aluminide alloys are a new class of advanced materials that offer improved high-temperature performance over traditional stainless steels and many nickel-based superalloys. Oxidation resistance and other attributes make nickel aluminides attractive for many applications.

Two of these intermetallic alloys are currently available: castable, cold-workable IC-50 alloy, and castable, weldable IC221M, for dynamic applications. IC-50 is the basic alloy with minor alloying additions of boron and zirconium to improve ductility. IC-221M is more highly alloyed. Chromium additions improve the high temperature ductility; zirconium reduces solidification shrinkage and increases high temperature strength; and molybdenum increases low- and high-temperature strength.

The tensile properties of these alloys are very attractive, due to the long range order of the crystalline structure. The yield strength actually increases with temperatures up to 800° C, where it reaches a maximum of 724 MPa. A key property of nickel aluminide alloys is that their load-carrying ability actually increases as the service temperature increases.

At United Defense LP, the Exo-Melt process has proven successful in melting commercial heats of nickel aluminide alloys IC-221M and IC-50, most consisting of between 680 and 1,000 kg; however, larger heats could be accommodated. Cast parts have been poured in traditional green sand and air set moulds, as well as in Replicast. The latter process allows design flexibility and casting quality rivalled only by investment casting, because parting lines and cores are not required.

The governing economic consideration in the selection of heat- and corrosion-resistant alloy castings is the cost per hour at operating temperatures. Equipment downtime can result in a loss of production that is far more expensive than the cost of the alloy. High-temperature castings manufactured from nickel aluminides, as opposed to the H-series and nickel-based alloys, may be redesigned to take advantage of their inherent strength at high temperatures, and to reduce component size, mass and cost.

The high-temperature performance of these nickel aluminide alloys is similar to that of ceramic materials. Their high-temperature strength, oxidation resistance, carburization resistance and fatigue properties make them ideal candidates for such applications as hardware for high-temperature furnaces, metal-forming tooling, and oil and chemical processing equipment. (Extracted from *Advanced Materials & Processes, 11 95*)

Nickel-free gold alloys

A series of 34 nickel-free white gold alloys has been developed by Handy & Harman, Art Products Group (East Providence, RI, USA), that is said to eliminate allergic reactions caused by the leaching of nickel from 10 karat gold alloys. White gold alloys were originally developed to provide a less costly precious metal alternative to platinum. Although nickel is a good whitener, and, when combined with copper, provides good workability and castability, a proportion of the general population has allergic reactions to it.

According to the company, the 10 karat alloys were prepared with palladium and germanium, as well as the commonly used silver and zinc. The two most promising alloys contain about 51 per cent silver and 5 per cent palladium, and either 2 per cent zinc or 2 per cent germanium. In addition to producing good cast pieces, they behave well in finishing operations such as grinding, tumbling and polishing. Another alloy contains both germanium and zinc, which results in enhanced hardness. (Extracted from *Advanced Materials & Processes, 5 94*)

High aluminium ferritic stainless alloys

Scientists at Texas Instruments, Metallurgical Materials Division (Attleboro, MA, USA) have produced extremely refractory high-aluminium ferritic stainless alloys by reacting component metals after forming into catalytic converter substrates. This materials synthesis technology enables low-cost manufacture of high-temperature alloys that are so difficult to fabricate by conventional means that they have been limited to specialized applications.

The technology involves roll-bonding layers of commercially pure aluminium to a centre layer of chrome-bearing stainless steel. This clad metal is then easily cold-rolled to foil, and formed into catalytic converter structures. The clad foil can, in fact, be formed into any shape possible with stainless steel.

Thermal treatment after the substrate is fabricated transforms the three-layer clad metal into the substrate alloy. Initial thermal treatments can create composition gradients in the material. For example, a high concentration of aluminium can be developed on the surface, and less at the core of the foil. If thermal treatment takes place in air, an aluminium-oxide surface will form concurrently as aluminium diffuses into the steel base; the alloy body and aluminium-oxide surface are formed together. Alternatively, the material can be formed first, with or without a composition gradient, by thermal treatment in vacuum or argon. The aluminium-oxide surface is then formed during a secondary heat treatment in air.

Close control is permitted during the process of the aluminium concentrations, both at the surface and within the alloy. It also permits development of a coating of aluminium oxide whiskers, which provide a vastly increased surface area for the platinum catalyst compared with a flat, whisker-free surface.

One problem with conventionally produced substrate metal is that formation of aluminium oxide at the surface depletes aluminium in the immediately adjacent base metal. Moreover, catalytic converter manufacturers prefer a higher aluminium content (to grow a thicker aluminium oxide surface coating), than is possible with conventionally produced high-aluminium ferritic stainless steel. This new process circumvents this problem by placing thicker layers of aluminium on the top and bottom surfaces of the chrome steel. Trials have shown that, except for the higher aluminium content, the final catalytic substrate materials are metallurgically indistinguishable from alloys produced by conventional methods. Examinations also show no discernible difference in either microstructure or alloy uniformity.

The higher aluminium content in the new foil, however, leads to another advantage over conventional materials. Catalytic converter materials face continuous high-temperature oxidation conditions from the engine exhaust gases. With this new foil, oxidation resistance of the catalyst substrate is enhanced significantly.

This new technology overcomes other limitations of conventional technology. For example, the compositions of conventionally produced metal substrate foils in Europe and the United States of America are limited by the material's fabricability. Aluminium content must be limited to 5 per cent, or the material simply breaks apart during forging and rolling. The company says that this is not the case with the substrate metal produced by their synthesis process. Metallurgists can choose a higher aluminium content for a longer-lasting catalyst substrate. Researchers have further found that rare-earth elements contained in catalyst materials can be easily added to the chrome steel, suggesting that further alloy development is possible. As a result, this new technology is prompting development of alloys for even higher temperature operation, because the process eliminates fabrication limitations caused by composition, particularly high aluminium content that makes the material extremely difficult to form.

Public pressure for longer catalyst life and the technical need for materials that are stronger than conventional ceramic substrates, and can operate closer to the engine exhaust manifold, are forcing auto manufacturers towards metal substrates. Many auto makers have already converted to metal catalyst substrates.

Pollution reduction is another principal force behind the conversion trend. Metal substrates provide faster "light off" than conventional ceramics. In other words, metal eliminates much of the warm-up time ceramic catalysts need before they reach operating temperatures. Auto emissions output is at its peak when a car engine is cold at startup which is a major source of pollution, particularly in cities where there is so much on-off cycling of engines.

Metal substrates are stronger than ceramics, and have greater resistance to thermal shock, which is a major cause of catalyst failure, and vibration. They are easier to fabricate into designs that will fit closer to the engine exhaust manifold. However, the restraining factor for the auto industry is that, until now, metal substrates cost more than ceramic. This new technology, it is claimed, can produce these materials at a cost competitive with existing ceramic converters. (Extracted from *Advanced Materials & Processes, 1 95*)

Oxidation-resistant steel for catalytic converters

A 20 per cent chromium-5 per cent aluminium steel with small additions of zirconium and lanthanum reportedly has a lifetime three times that of conventional 20Cr-5Al steels in catalytic converter substrate applications. Designated River Lite 20-5USR, this stainless steel alloy was developed by Kawasaki Steel Corp. (Tokyo 100, Japan) to improve the high-temperature oxidation resistance of catalytic converters placed in the high-temperature zone near the engine.

According to the company, the lifetime of the steel foil increases with increasing lanthanum content up to 0.08 per cent, with lifetime practically constant with additions above that amount. The addition of 0.05 per cent zirconium achieves maximum life, but higher amounts decrease life. The toughness of hot-rolled sheet is highest when the ratio of zirconium to the total of carbon and nitrogen is approximately equal to one. The tensile strength of the Alloy is reported to be 570 MPa. Its lifetime in air at 1,200° C is 600 ks, compared with 200 ks for a 20Cr-Al Alloy without the lanthanum and zirconium additions. (Extracted from *Advanced Materials & Processes, 2 95*)

Nickel-cobalt-iron superalloy for turbine engines

Inconel Alloy 783 has been developed by Inco Alloys International (Huntington, WV, USA) for applications such as casings and rings for compressors, turbines, and exhaust systems. The reported properties include a coefficient of thermal expansion 20 per cent lower than that of Inconel Alloy 718, density of 7.78 g cm^{3} and resistance to stress accelerated grain boundary oxidation very close to that of alloy 718. Oxidation resistance is claimed to be excellent up to 700° C.

The alloy is a low coefficient-of-thermal-expansion superalloy strengthened by precipitation of γ' (ordered face-centred cubic) and β (body-centred cubic) aluminide phases in a nickel-cobalt-iron-base austenitic matrix. Its low expansion coefficient is caused by the ferromagnetic nature of the bonding between nickel, iron and cobalt atoms. The chromium content is limited because it raises thermal expansion over a range by reducing the Curie temperature. Therefore, the alloy achieves resistance to general cyclic oxidation and stress accelerate grain boundary oxidation embrittlement primarily through an aluminium addition sufficient to produce a three-phase microstructure of γ, γ' and β.

According to the company, processing characteristics of Alloy 783 are similar to those of Alloy 718. Forging billet, rounds and flats are made by vacuum induction melting, vacuum arc remelting and hot working. (Extracted from *Advanced Materials & Processes, 2 95*)

Aluminium-polypropylene sheet reduces weight by 30 per cent

A laminate of polypropylene (PP) sandwiched between layers of aluminium has been developed by Hoogovens Hylite BV (Ijmuiden, the Netherlands), for automotive applications in which low weight and flexural rigidity are important. Called Hylite, the material is said to be 65 per cent lighter than steel and 30 per cent lighter than aluminium for the same stiffness. Formability is claimed to be comparable to that of aluminium sheet, and it also has excellent sound-damping capability.

The material consists of a core of PP 0.8 mm thick covered on both sides with 0.2 mm of aluminium. The alloy 5182-0 is used for applications in which deep drawing is required. For applications in which the material is not formed, alloy 5182-H18 is selected as it is harder. Polypropylene was selected as the core because it can withstand the heat of painting processes. Rigidity, dentresistance, and formability can be adjusted during the manufacturing process by selecting the thickness of each layer, within certain tolerances.

Hylite can be formed using relatively low forces, allowing the use of inexpensive tooling. It can be worked using equipment designed for steel or aluminium, and has similar machining characteristics to those of aluminium. However, it cannot be welded. Typically it is joined by adhesives in automotive applications, but mechanical methods such as bolts, rivets and staples can also be used. (Extracted from *Advanced Materials & Processes*, 2/95)

Lead-free brass alloys

The Copper Development Association (New York, USA), and the Brass and Bronze Ingot Manufacturers (New York, USA) have announced ongoing development of a family of lead-free brass casting alloys. These alloys are said to contain small additions of selenium and bismuth to provide good castability and free-machining performance. Both the semi-red brasses used in sand castings and the yellow brasses used in permanent mould castings are being studied.

Although the alloys are reported to be only developmental at the moment, they will be supplied in limited quantities for trials by foundries on the condition that the performance data can be shared with the development group. Work is proceeding to define the optimum selenium levels and the tests required to verify the mechanical properties of the alloys. (Extracted from *Advanced Materials & Processes*, 2/95)

Aluminium-lithium extruded and forged

The EH101, a new European helicopter, has reportedly been designed specifically to use the Lital 8090 aluminium-lithium alloy developed by Alcan Specialty and Aerospace Ltd. (Birmingham, UK). The alloy is used in sheet form for the fuselage skin, and is extruded for cabin floor and door components. It is cold-compressed forged for fuselage frames and undercarriage parts.

The company claims that Lital saves up to 9 per cent in weight when it is directly substituted for conventional aluminium alloys, and it reduces weight by up to 13 per cent when the component is specifically designed for the alloy. Further, it offers a 9 per cent increase in stiffness. (Extracted from *Advanced Materials & Processes*, 2/95)

3. ALLOYS FOR AUTOMOTIVE APPLICATIONS

Stainless steel auto exhaust system

With the ever-increasing price of automobiles, durability and reduced operating costs have become major concerns in many countries. For many years, exhaust systems were considered to be parts that were routinely replaced every few years. They are now considered non-replaceable for at least five or six years.

Throughout the 1980s, the only stainless steel on most car exhausts in the United States was in the downpipe and catalytic converter, these were due to government warranty mandates. Today, most car exhaust systems are almost entirely stainless.

The exhaust system can be basically divided into two parts: a hot end and a cold end. The hot end includes the exhaust manifold, downpipe, and catalytic converter. The hot end is considered part of the vehicle's emission-control system, and therefore comes under US government-mandated warranties.

The cold end, which includes the resonator, intermediate pipe, muffler, and tail pipe, has a durability or warranty target chosen by the car maker. It is this cold end section that has seen the most dramatic upgrade of life expectancy and materials in recent years.

The need for greater exhaust system durability has led to a dramatic increase in the use of stainless steel, particularly ferritic 11 per cent Cr alloys. In more demanding heat and corrosion areas, higher-alloyed 17 to 20 per cent Cr ferritic alloys, austenitic Cr-Ni materials, and even aluminium coated ferritic stainless alloys have been used. A trend towards stainless and away from aluminized carbon steel is taking place world-wide.

In order to maximize durability whilst reducing component costs, specialty steel researchers have found certain ambient considerations practical from the perspective of the hot end, cold end, and flange hanger rod component design.

In the hot end, exhaust parts remain hot and dry. Material properties, including oxidation resistance, strength at operating temperatures, and coefficient of expansion are important. A move towards higher chromium, silicon, aluminium, and niobium alloys, coupled with improved design, has reduced thermal fatigue fractures, oxide spalling, and defoliation in the hot end.

In the cold end, lower temperatures lead to interior condensate formation and more exterior salt corrosion. Studies undertaken by Armco (Pittsburg, PA,USA) have shown that the move toward stainless exhaust systems has dramatically reduced the frequency of exterior salt failures.

Condensate corrosion, which is a problem aggravated by corrosive chemicals in the condensate, remains the chief concern in stainless exhaust systems. Researchers at Armco are working with exhaust system designers to provide alloys with the optimum combination of corrosion resistance and formability.

The demand for greater durability has also increased the use of stainless in flanges and rod hanger configurations, which were the last stronghold of bare carbon steel in many exhaust systems. Cost and coefficient of expansion have hindered the use of austenitic stainless steels in stamped flanges, but a higher nickel version of Type 409 now appears to be a cost-effective solution.

The most frequent exhaust system component-forming problems have resulted from making running component changes from carbon to stainless. Tooling designed for carbon seldom adapts unchanged to forming stainless parts, and variations in chemistry and mechanical properties between stainless producers requires adjustment to welders, tube benders and draw presses between each master coil. (Extracted from *Advanced Materials & Processes 1 95*)

Aerospace alloy in racing car exhaust

The AerMet 100 alloy, which was developed for aerospace applications by Carpenter Technology Inc., (Reading, PA, USA), has reportedly been selected to replace 300M high-strength steel in the rear-axle half-shaft of a racing car. Changes in the wind-flow aerodynamics caused by a redesign of the car, led to the passage of superheated exhaust gases over the shaft, heating it to 480-600° C. Several shafts failed during early tests of the redesigned vehicle, prompting engineers to investigate materials that could operate at these temperatures.

The initial testing of AerMet 100 showed that it would withstand the high temperatures for at least 10 hours, which is more than triple the time required for an 800 kilometre race. Following design improvements, the car company found that the shaft could be run for 3200 kilometres before being retired from service. The alloy solved the exhaust-gas problem and met all safety requirements.

AerMet 100 is a nickel-cobalt steel strengthened by carbon, chromium, and molybdenum. Its ultimate tensile strength is 1965 MPa, yield strength is 1725 MPa, elongation is 14 per cent, and Young's modulus is 195 GPa. Other applications include bolts, driveshafts and crankshafts, springs, and fasteners. (Extracted from *Advanced Materials & Processes 4 94*)

Magnesium castings for auto applications

Magnesium is the Earth's eighth most abundant element. It is found in a variety of ores, such as magnesite and dolomite, but its most common source is the world's oceans, where each cubic kilometre of seawater contains 1.3 million tons of magnesium.

The technology for producing magnesium alloys is mature. Major producers extract the element electrolytically from an ore and or salt water with electricity being a larger cost factor than raw materials. Unlike many other materials, magnesium alloy prices are very stable, and have not appreciably changed over the past several years. Some reasons for this stability include a large, mature material supply base, well-developed secondary markets, such as scrap recycling, and the fact that magnesium is not traded on any commodity exchange. The materials selection process is a major beneficiary of stable pricing. When new applications require three or more years to implement, the last thing an automotive product planner needs is fluctuating prices. There are other factors in addition to price stability, which are causing a growth in the use of magnesium alloys for structural automotive applications. These are: mass reduction; reduced systems cost; properties of magnesium, and corrosion behaviour.

Mass reduction: Magnesium is most commonly associated with lightweight components. In general, low-density materials have been rigorously evaluated for automotive applications for many years. Standards on fuel economy are putting additional short- and long-term pressure on automotive companies to simultaneously cut product cost and boost fuel economy.

A basic route to improved fuel economy is weight reduction, where magnesium shines. However, weight reduction alone may not be the primary means of meeting these standards. Increasing powertrain efficiency will also lead to reduced costs and better fuel economy. For example, lighter rotating and reciprocating parts have lower momentum or inertia, which, in turn, reduces the energy needed to keep the system in motion. Magnesium castings have been successful in this regard.

Reduced systems cost: Reducing development and tooling costs are other means by which to reduce cost. Magnesium can be cast into relatively thin, design-flexible and property-efficient shapes. As such, magnesium die castings are being designed to consolidate complex, part-intensive assemblies; smaller numbers of parts require less logistic effort. Smaller numbers of parts also normally translate into less warehousing and transportation costs for the end user.

Alloy properties: Key mechanical properties of magnesium alloys show that for a given casting type, the tensile and yield strengths will generally increase with increasing aluminium content, whereas the elongation and impact properties will generally increase with decreasing aluminium content. The current magnesium applications at the main automotive makers are die castings. 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. It may, therefore, be important to consider during the development stage, the metallurgical differences between castings produced by different methods.

Corrosion behaviour: Today's high-purity magnesium alloys have a corrosion resistance in the salt-spray test better than that of the competing aluminium die casting alloy A380.0 and far superior to that of low-carbon steel. However, galvanic corrosion is a potential problem because magnesium is anodic to other common metals used in automotive structures. Even alloys of the highest purity will not perform well in galvanic corrosion situations unless appropriate design measures are taken.

In the past, engineers relied primarily on previous experience and successful applications to select materials for structural parts. Now, however, automotive materials specialists are giving greater attention to selection based on "property efficiency" considerations.

The structural efficiency of a part is defined as the ratio between the load it can support and its weight. When a current part design and loading condition are considered relatively stable, the intrinsic properties of materials can be objectively evaluated and compared. When these attributes are combined, the derived property efficiency is called the "strength-to-weight-ratio", or the available strength per unit weight of a given material.

An important criterion for evaluating structural efficiency is the relative ability of a material to resist deflection or bending during service. A simplified approach compares the product of a material's elastic or Young's modulus, and the part's cross-sectional area or moment of inertia. To achieve uniform deflection for a given set of materials, the moment of inertia of the part must be changed. In most cases, this can be accomplished by increasing the relative height of a given section, or by using either ribs or a waffle or honeycomb pattern.

It is also possible to determine the stiffness efficiency of a material, which, for a uniform cross-section, is defined as the ratio of elastic modulus to density, and is commonly called the stiffness-to-weight ratio.

Previously, magnesium was usually considered only as a direct replacement for aluminium castings. Consequently, substitution was more or less straightforward. Today, engineers are learning that magnesium can also replace other materials and processes. In addition to aluminium, magnesium has been substituted for cast iron, plastics, zinc, and steel. These could include: transfer cases; lock housings, and knee bolsters. (Extracted from *Advanced Materials & processes 6/94*)

4. ALLOYS FOR ELECTRONICS

Specialty steelmakers winning new users

Specialty steel producers of alloys, principally nickel-iron, are facing new challenges for a market with the diminishment of the previous military market as this decreases its requirements. These efforts are showing some signs of success, but are hampered by a low industry profile, imports, high engineering and production costs, and excess production capacity, particularly in the USA. Even when people are aware of the unique properties of alloys, they can be jolted by the price.

However, as electrical applications and electronics become more sophisticated, manufacturers are discovering that standard metals no longer adequately fit their needs. For instance, in automobiles, where electronic systems are becoming more numerous and sophisticated, new alloys are needed that can withstand heat, vibration and electromagnetic radiation while contributing to the overall drive towards component miniaturization.

The unique properties that these specialty steel alloys exhibit depend on how they are processed and, in the case of nickel-iron alloys, on the ratio of nickel to iron. Iron-rich nickel alloys are used when controlled-expansion properties are needed. More nickel, however, provides improved magnetic properties.

The controlled-expansion group of alloys, as with specialty steels in general, is not widely understood outside the industry itself. However, controlled expansion materials are widely used, for instance, computer chip manufacturers use the alloys to provide a hermetic seal that keeps silica chips from contact with air. These metals are used for the seals because they have very unique expansion characteristics and are designed to match the expansion rates of certain types of glass and ceramics.

The qualities of controlled expansion metals are also valuable in thermostats, where metals with low expansion mated to high-expansion alloys bend in response to temperature variations. These simple bimetallic devices perform a variety of tasks: turning off overheated appliances; controlling circuit breakers and regulating automobiles.

A strong market segment exists for electronic transformers where nickel-iron alloys are stamped into laminations which are then stacked and made into transformers. An increasingly popular transformer-like application involves ground-fault circuit interruption, which is becoming a requirement in new housing starts. Ground-fault interrupter plugs, which contain two magnetic cores are made from nickel-iron alloy materials, sense a spike in the circuit, and then shut the circuit off so that no-one is electrocuted.

The future looks promising for magnetic bearings. While normal contact bearings in motors can wear out, or contaminate other materials through contact, magnetic bearings touch no moving parts. A magnetic bearing supports an object, such as a rotating shaft within a magnetic field. The shaft is suspended, and its position controlled, without physical contact. The potential advantages over conventional oil-lubricated bearings include: no friction and wear, low vibration and noise, unlimited service life and insignificant power loss. The technology has only become practical with advances in electronic feedback controls. For certain critical applications, these magnetic bearings could have a very significant place in the future.

Another area with a good deal of potential is the electromagnetic interference (EMI) shielding market. This field is growing due to efforts by a wide range of manufacturers (automotive, aircraft and television tube makers), to cram more electronics into smaller spaces. Shielding has long been used in a variety of military equipment because of concerns about electromagnetic interference from surrounding equipment. Inco (USA) are currently developing an electro-deposited nickel foil, that would compete with aluminium and copper foils in providing protection from electromagnetic interference for products like notebook computers. The foil was developed for solar energy collection, however, with the stagnation of that market, it is being put to other uses.

Another strong market for magnetic alloys is theft-detection equipment. Detection devices found in retail shops, video stores and libraries employ metal tags consisting of two strips, one made of a soft magnetic material and the other a permanent magnet. These tags send out unique high-frequency magnetic signals when activated, triggering an alarm. These tags can also be used to track inventories.

The products mentioned above only touch lightly the hundreds of specialty alloys that have been developed to satisfy specific market needs. The number of these niche markets will only grow as electronic applications continue to proliferate and as manufacturers become better at specifying their specific alloy needs, which can range from better corrosion resistance and improved machinability to enhanced magnetic and expansion properties. (Extracted from *American Metal Market, 16 May 1995*)

5. NEWS FROM RESEARCH AND DEVELOPMENT CENTRES AND COMPANIES

Al-Li alloy takes on carbon/epoxy composites

The Aluminum Co. of America (Alcoa), (Pittsburgh, PA, USA), has developed an aluminium-lithium aerospace alloy which is reported to have 200 per cent higher fatigue-crack-growth resistance and 35 per cent higher fracture toughness than aluminium alloy 7075-T651, the conventional material for upper wing and lower stabilizer skins. Designated C-155, the alloy is also said to be stronger than aluminium alloy 2024-T351, which is the conventional material for these parts.

The company developed this new alloy in response to the selection of carbon epoxy composites for applications in the vertical stabilizer and tailplanes of the Boeing 777 and Airbus A330 340. Alcoa commissioned Vought Aircraft Co., (Dallas, Texas, USA) to carry out a study to find out how the performance of C-155 compares with that of conventional aluminium alloys and with carbon epoxy composites, through evaluating horizontal stabilizers made of each of the three materials.

Results showed that for equal performance, C-155 provided direct weight savings of 300 kilograms over conventional aluminium alloys, or 12.3 per cent of the original tailplane's total weight. Although the overall weight of the C-155 part was very close to that of the composite part, considerable cost savings per kilogram of weight were achieved.

For more information contact: Alcoa-Atlanta, 1050 Crowne Point Parkway, Suite 1650, Atlanta, Georgia 30338, USA. (Extracted from *Advanced Materials & Processes 8/94*)

Lead-free bronze alloy

A lead-free bronze alloy that reportedly cuts machining times in half has been developed by Magnolia Metal Corp., (Omaha, NB, USA). Designated Free B-1 Bronze, the alloy contains bismuth in place of most of the lead, containing about 0.1 per cent residual lead, as well as copper and tin. In addition, the alloy contains no zinc, thus increasing its corrosion resistance.

According to the company, the alloy can take higher loads and shock than the standard CDA 932 hard bearing alloy. Although the material cost of Free B-1 is higher than leaded alloys, it only takes half as much time to machine, thus resulting in an overall cost reduction of about 10 per cent. The coefficient of friction of the new alloy is also said to be within 15 per cent of conventional leaded bearing alloys, and it offers improved anti-galling properties. The reported tensile yield strength of the alloy is 140 MPa, ultimate tensile strength is 280 MPa, Brinell hardness is 80, and elongation is 30 per cent. Applications are for water pumps, food-processing equipment and other applications where the lead content must be minimized.

For more information contact: Magnolia Metal Corp., P.O. Box 19110, Omaha, Nebraska 68119, USA. (Extracted from *Advanced Materials & Processes 1/95*)

Stainless steel alloy offering 40 per cent higher rupture strength

Sumitomo Metal Industries Ltd., (Tokyo, Japan) has developed a stainless steel reported to have creep rupture strength 40 per cent higher than TP347H. Designated Super 304H, the alloy is basically an 18-8 steel; copper, niobium, and nitrogen additions are said to improve creep-rupture strength with the combination of niobium and nitrogen refining the microstructure.

According to the company, the alloy is also highly corrosion resistant, especially when exposed to steam, having apparently undergone more than five years of testing in commercial boilers.

For more information contact: Sumitomo Metal Industries Ltd., Ote Center Ltd., 1-3 Otemachi 1-chome, Chiyoda-ku, Tokyo 100, Japan. (Extracted from *Advanced Materials & Processes 1/95*)

23,000 kilogram ingot of nickel aluminium bronze

A project has been undertaken to make a 170 centimetre nickel-aluminium-bronze ingot weighing 23,000 kilograms by Electralloy associated with Scot Forge, for the first time. This material was manufactured to the requirements of ASTM B150-92 copper alloy. The high aluminium content (9 per cent) in combination with a preferred silicon maximum of 0.10 per cent made the production of this alloy by electric arc furnace melting and argon oxygen decarburization refining extremely challenging. As neither organization has experience with the manufacture of the alloy using these technologies, a 230 kilogram induction heat was first cast to help determine some of the processing parameters required to produce a sound casting.

The UNS C63200 exhibits rapid solidification as well as a high tendency to oxidize. In addition, the reactivity of aluminium in the alloy with the various constituents of refractory, atmosphere, bottom-pour powders, and hot topping compounds was a concern. Special care was taken to ensure that the proper flux was utilized and would perform its function without inclusions or contamination of the ingot, so as to accommodate the extremely low pouring temperature of the alloy. As a result of the studies carried out, melt practices, as well as the design of the refractory materials were changed. A final silicon content of 0.066 per cent was determined. The 170 centimetre diameter ingot was successfully bottom poured and then forged to an intermediate size in preparation for final manufacturing into a ring over 6 metres in outside diameter.

For more information, contact: Electralloy, G.O. Carlson Inc., P.O. Box 381, Oil City, PA 16301, USA. (Extracted from *Advanced Materials & Processes 1/95*)

Functionally gradient Al-based amorphous alloys

A research team at the Institute for Materials Research, Tohoku University, have created aluminium-based amorphous alloys with a gradually changing composition in the depth direction. The alloys are made by the reactive sputtering method with the nitrogen concentration controlled by the voltage. Comparison with single-phase compositions shows the advantages of the functional gradient: the heat resistance is almost doubled; the abrasion resistance was increased several times; the hardness increased by a factor of approximately 10, the impact resistance was also much enhanced.

Functionally gradient materials are a new type of materials with the composition gradually changing to acquire novel functions that conventional homogeneous materials cannot achieve. The new materials are amorphous Al-Ti, Al-Zr, and Al-Cr alloys, made using the reactive sputtering method with a magnetron. The new alloy is deposited on a substrate in argon gas with nitrogen added. The nitrogen concentration is controlled to make the alloy composition gradually change.

With the gradient in the composition, the new amorphous alloys demonstrate the favourable qualities of the individual single-phase alloys, without the disadvantages. The Al-Ti alloy begins with an amorphous metal and ends with crystalline ceramic material. The Al-Zr alloy is a metal whose composition changes gradually. The Al-Cr alloy begins with an amorphous metal and gradually changes into an amorphous ceramic material.

Each functionally gradient alloy has advantages over conventional single-phase amorphous alloys. The temperature resistance has nearly doubled to 200-300° C. The abrasion resistance has increased to a few times as much as before. The product consists of a functionally gradient surface layer and an underlying soft amorphous alloy, which acts as a damper. The deposition thus has a much enhanced impact resistance.

The invention of functionally gradient alloys may lead to the development of new advanced amorphous alloys that amalgamate the advantages of different amorphous alloys.

For further information, contact: Institute for Materials Research, Tohoku University, 2-1-1, Katahira, Aoba-ku, Sendai City, Miyagi Pref. 980, Japan. (Source: *JETRO, May 1994*)

Corrosion resistant amorphous alloys development

Mitsui Engineering & Shipbuilding Co. Ltd., has developed various kinds of amorphous alloys that are so-called "dream metals" featuring characteristics not displayed by generic crystalline metals, and has developed applications for these alloys by introducing the sputtering method. By improving the technologies for manufacturing these amorphous alloys, the company succeeded in developing a new type of amorphous copper alloy that combines an excellent corrosion resistance and anti-bacterial effect. This alloy was commercialized under the brand name "Amorphous Insole".

The principal characteristics of this insole are (1) a high anti-bacterial and offensive odour prevention effect due to the action of copper ions, (2) resistance to oxidation despite being a copper alloy, (3) excellent metallic lustre and heat insulation effect, and (4) excellent humidity absorption, gas permeation and cushion effect. The amorphous alloy coated non-woven fabric is applicable not only as an insole, but as a material for producing leather footwear inner materials, and the material for manufacturing sports shoes and slippers. It is also highly promising for preventing the proliferation of various bacteria in foods and drugs, and for the manufacture of various clothes, bedding, kitchens, and bathrooms.

The adhesion of marine organisms causes problems due to the proliferation and adhesion of barnacles on the surfaces of cooling water intakes and outlets of power stations, so various methods are under study for removing them with chemicals, using materials which prevent adhesion, and the use of special types of paints.

To confirm the effectiveness of the amorphous non-woven fabric for this application, a study was carried out with this fabric and a comparative material for a period of approximately 50 days, in summer at places where barnacles are likely to adhere, and the adhesion of marine organisms was surveyed. Hardly any marine organisms adhered on the surfaces of the non-woven fabric, and the fabric retained its metallic lustre. Meanwhile, barnacles adhered to the entire surfaces of the materials made of stainless steel, slate, and non-coated non-woven fabric. In addition, anti-bacterial tests were conducted on the amorphous non-woven fabric with *E. coli*, confirming that the new fabric has excellent anti-bacterial effects against *E. coli*, as well as ringworm and yellow phylococcus. (Extracted from *JETRO FY 1993*)

Amorphous coating technology development

Among the different facilities and equipment for reprocessing plants, the recovery container for acid vapours is used in environments using high-temperature, concentrated HNO_3 solutions containing metal ions. Therefore, the structural materials for these containers must have corrosion resistance when used in these harsh environments. A study of titanium or zirconium alloys was made to improve the safety of stainless steels, such as types S304L and 310ELC. In parallel with attempts to convert these structural materials into excellent corrosion resistant materials, efforts are being made to coat excellent corrosion resistant amorphous metals on the surfaces of stainless steels.

Mitsui Engineering & Shipbuilding have developed a nickel-valve metal amorphous alloy that has an excellent corrosion resistance in environments consisting of boiling concentrated hydrochloric acid or nitric acid. To enable the amorphous coating technology to be applied to reprocessing plant installations and equipment through using a sputtering method: the company selected an amorphous metal that showed excellent corrosion resistance in nitric acid by conducting various performance tests such as immersion corrosion tests on the selected amorphous metal, corrosion tests under heat transfer conditions, thermal cycle corrosion tests, and galvanic corrosion tests.

Results of the tests showed that the Ta-based amorphous coating technology is highly effective for extending the service lives of reprocessing facilities and equipment, so full-scale application of this amorphous coating technology to reprocessing facilities and equipment is expected. Plans are under way to conduct long-term tests to further improve the reliability of this new technology. (Source: *JETRO FY 1993*)

Austenitic grade stainless steel resists chlorine dioxide

The world's pulp and paper industry must reduce, or totally exclude, chlorine bleach from its processes to eliminate the traces of dioxin remaining in the pulp. The short-term solution is a much more intensive use of chlorine dioxide as a bleaching agent, because it does not lead to dioxin formation. The problem with this approach is that chlorine dioxide at the high levels required is extremely corrosive.

At the moderate pH levels reached during paper production, high molybdenum nickel-base alloys suffer from transpassive corrosion, a severe form of uniform attack that significantly reduces the effective service life of the equipment. To deal with the corrosion mechanism of chlorine dioxide over the full range of service conditions, Avesta Sheffield (Schaumburg, IL, USA), has developed 654 SMO, a high-molybdenum, high-nitrogen austenitic stainless steel.

Several years ago the company established a research programme to develop an austenitic stainless steel having corrosion resistance superior to that of the 9 per cent molybdenum nickel-base alloy 625. The new alloy 654 SMO, has chloride resistance comparable to that of the 15 per cent molybdenum nickel-base alloy C-276.

The 654 SMO steel is already covered in ASTM specifications for flat-rolled products, with specifications for other product forms to follow soon. The company is starting to establish availability from inventory for a full range of product forms, together with intensive technical support for users. In addition, the company has developed appropriate filler materials and procedures for several welding processes.

For further information, contact: Avesta Sheffield, Woodfield Corporate Centre, 425 Martingale Road, Suite 2000, Schaumburg, IL 60173, USA. (Extracted from *Advanced Materials & Processes 1 95*)

Superferritic stainless steels

The superferritic stainless steel Al 29-4C alloy shows excellent resistance to chloride ion pitting, crevice corrosion, and stress corrosion cracking. This high corrosion resistance makes it suitable for use in a wide variety of corrosive environments. At the same time, it is economical because of its low alloy content, compared with other high-performance alloys, and conventional melting methods.

Fe-Cr-Mo alloys with 29 per cent chromium have excellent resistance to chloride pitting and crevice corrosion. Both AL 29-4 and AL 29-4-2 are highly resistant to corrosion in a variety of oxidizing environments. The nickel-containing AL 29-4-2 alloy also has good resistance to corrosion in dilute reducing acid environments.

Both alloys possess fully ferritic structures. Ferritic stainless steels exhibit a transition from ductile to brittle impact behaviour as the test temperature is reduced, and increasing test-section thickness raises the temperature for this transition. These alloys were designed to mitigate this effect through restriction of carbon and nitrogen levels to extremely low levels, which could only be attained through the use of high-purity raw materials and vacuum melting, making these alloys expensive to produce.

The AL 29-4C alloy, a conventionally melted alloy designed by Allegheny Ludlum, maintains the high level of chloride pitting and crevice corrosion resistance of the vacuum-melted alloys at lower cost. The stabilized composition allows production using conventional argon-oxygen decarburization refining of standard raw materials. However, this economy is achieved at the cost of reduced toughness.

Although light-gauge AL 29-4C has good toughness, material thicker than approximately 2.5 mm may have a Charpy V-notch ductile-to-brittle transition temperature as high as room temperature. Consequently this alloy is not available at thicknesses greater than about 1.5 mm.

The 29Cr-4Mo alloys are very resistant to chloride pitting and crevice corrosion. One test for corrosion resistance in high chloride environments is the ASTM G-48 Practice B ferric chloride test. In this test, inert polytetrafluoroethylene crevice forming blocks are held against the sample, which is then immersed in a 10 per cent solution of ferric chloride hexahydrate. After immersion, the alloy sample is removed, weighed, and examined for evidence of corrosion attack. In order to rank the materials according to temperature, the test is repeated at successively higher temperatures until crevice corrosion attack of the sample is observed.

The highest temperature at which no attack is observed is called the critical crevice corrosion temperature (CCCT). Experience has shown that stainless alloys that exhibit ferric chloride CCCTs above room temperature are usually resistant to crevice corrosion in sea water. The 29Cr-4Mo alloys, with CCCT of 50° C would thus not be expected to be attacked in this environment. In addition, the low nickel contents of these alloys gives them high resistance to chloride stress corrosion cracking.

Some of the high chloride environments in which this alloy has been successfully used include both sea water-cooled and brackish water-cooled surface condensers in electrical utility power plants. Other AL 29-4C heat exchangers operate in geothermal brine, which is among the most corrosive of the high-chloride environments. The alloy has also been used in a range of petroleum refining applications because of its resistance to chloride-induced pitting, crevice corrosion, and stress-corrosion cracking.

For more information, contact: Allegheny Ludlum Corp., Tech. Center, Alabama & Pacific Avenues, Brackenridge, PA 15014-1597, USA. (Extracted from *Advanced Materials & Processes 1 95*)

Dual-phase alloy introduced

Duracorr is a new steel based on the familiar cold rolled ferritic grade Type 409, and the common martensitic plate grade Type 410. Developed by Washington Steel, it exhibits a combination of hardness, strength, toughness, weldability, and formability with the corrosion resistance of a nominally 12 per cent Cr stainless.

The beneficial mechanical properties of the alloy are derived from a microstructure that is a dual-phase mixture of ferrite and martensite. At reheating temperatures (for rolling), the balanced composition of the steel provides for an approximately equal mixture of ferrite and austenite. During plate rolling, the microstructure is refined to grain sizes of ASTM No. 9 and finer. Hardenability of the austenite is controlled by the composition to provide for transformation to martensite during cooling to room temperature. Subsequent tempering of the plate provides minimum mechanical properties of 275 MPa yield strength and 455 MPa tensile strength with room-temperature Charpy values typically greater than 36 J. The dual-phase microstructure permits the steel to be welded without the severe grain coarsening common with ferritic stainless, as a result, welded fabrications have excellent toughness.

The company expect the alloy to replace carbon steel plate and sheet in many applications where low maintenance and longer performance life are beneficial.

For more information, contact: Washington Steel Lukens Inc., P.O. Box 3001, Coatesville, PA 19320-0911, USA. (Extracted from *Advanced Materials & Processes 1 95*)

Clean superalloys

At present, materials for the most demanding applications are produced either by multiple consumable arc melting and conventional hot working, or through the powder metallurgical route. Both these processes have limitations. The consumable arc melting route is not suitable for superalloys with higher temperature capabilities, because it is difficult to produce an ingot that can be hot worked without cracking and is free of undesirable macrosegregation. The powder metallurgy approach is usually taken to produce these alloys. Although powder metallurgy is used very successfully to produce many commercial superalloy components, the product is plagued with high production costs. As a result of these problems, activities have been undertaken to develop a process for producing a fine-grained, clean superalloy material using a single, economical process.

The direct processing of electroslag remelted superalloys into spray-formed preforms in a ceramic-free system offers the potential to eliminate inclusions and reduce overall process costs, while minimizing segregation and producing a fine scale microstructure characteristic of spray forming. As a result, the metal produced by this method is characterized by an absence of large, non-metallic inclusions, and the incorporation of a ceramic-free pouring system ensures that the resulting metal will remain clean.

The process requires that a short electroslag remelt crucible for refining metals is attached to a cold wall induction guide tube. The principle of operation of the system is similar to that used for cold-hearth induction heated crucible systems. Liquid metal is contained in a hearth of water-cooled copper palisades; the gaps between them permit sufficient thermal energy to be introduced, via RF induction heating, to prevent solidification of the liquid metal and to limit the thickness of the solid metal skull at the interface. The refined metal passes from the cold wall induction guide as a stream that falls to an open atomizer ring, where it is converted to a spray. The spray is solidified onto a rotating collector, which is slowly withdrawn as the solidified alloy builds up. The rapidly solidified material is more homogeneous and has significantly finer grain size than conventional cast ingots. The process should produce, in a single, direct process step from molten metal, clean, fine-grained preforms of the most highly alloyed superalloys, suitable for applications in the most demanding turbine engine environments.

For more information, contact: Research and Development, Teledyne Allvac, P.O. Box 5030, Monroe, NC 28111, USA. (Extracted from *Advanced Materials & Processes 1/95*)

Corrosion-resistant superalloy

The Inconel alloy 686 is a single-phase, austenitic, nickel-chromium-molybdenum-tungsten alloy. It is designed for outstanding corrosion resistance in a wide range of severe environments. The high nickel and molybdenum contents provide good corrosion resistance in reducing environments, while the high chromium level imparts resistance to oxidizing media. Molybdenum and tungsten also improve resistance to localized corrosion such as pitting. The low carbon content and other composition controls help minimize grain boundary precipitation to maintain resistance to corrosion in heat-affected zones of welded joints.

The alloy is a candidate for use in the most severe environments encountered in chemical processing, pollution control, pulp and paper production, and treatment of industrial and municipal wastes. Potential applications in chemical processing include heat exchangers, reaction vessels, evaporators, and transfer piping. In air pollution control, the alloy could be used for numerous components, including stack liners, ducts, dampers, scrubbers, stack-gas reheaters, fans, and fan housings.

The alloy further provides good mechanical strength, and is most often used in the annealed condition. It has good weldability and needs no post-weld treatment to restore corrosion resistance.

For more information, contact: Inco Alloys International, Huntington, WV, USA. (Extracted from *Advanced Materials & Processes 1/95*)

Large-diameter reforging billet

The design and manufacture of very large high bypass jet engines for the next generation of commercial aircraft has created a need for very large diameter reforging billets exhibiting uniform metallurgical characteristics. New jet engines are designed to use turbine and compressor disks so large that billet stock used for the forging process can exceed 35 centimetres diameter with input weights in excess of 450 kilograms.

The operating parameters of these rotating components makes the metallurgical quality of the starting billet as exacting as those specified for smaller sections. Development of a very large diameter triple melt (vacuum induction melt plus electroslag melt plus vacuum arc remelt), Udimet 718 billet, for use in several of the next generation jet engines has progressed well.

Udimet 718 is a widely used superalloy combining high strength with adequate thermal resistance and serviceability. It is traditionally produced as double melt, or triple melt, fine-grain billets up to 25 centimetres in diameter. This billet has been specified by the forging industry to allow production of ultra-fine-grain forgings, which exhibit a beneficial combination of high strength and ductility. The ability to use sensitive immersion ultrasonic inspection of billets, due in part to the fine grain size, is another benefit of the specialized thermo-mechanical processing.

For more information, contact: Special Metals Corp., Middle Settlement Rd., New Hartford, NY 13413, USA. (Extracted from *Advanced Materials & Processes 1/95*)

Single-crystal superalloy for turbine blades

The superior creep, mechanical and thermal fatigue properties of a single-crystal, nickel-base superalloy developed by Cannon-Muskegon Corp., reportedly allow jet engine blades to run at higher temperatures than possible with other single-crystal superalloys. The ability to run at higher temperatures and increased rotational speeds improves fuel efficiency and provides higher thrust-to-weight ratios in jet turbine engines. Strong resistance to oxidation and improved coating performance allows thinner air foils, which increases operating efficiency.

The tensile strength of this CMSC-4 alloy at 760° C is 1170 MPa, yield strength is 965 MPa, elongation is 12 per cent, and reduction in area is 18 per cent. The company says that CMSX-4 has a stress-rupture advantage of 36° C over earlier single-crystal superalloys, and provides useful operating strength up to 1165° C.

Rolls-Royce (Derby, UK), announced that its new Trent 800 engine, which is equipped with CMSX-4 turbine blades, has achieved a new world record thrust level of 47.2kN.

For more information, contact: Cannon-Muskegon Corp., Subs. of SPS Technologies, P.O. Box 506, Muskegon, MI 49443-0506, USA. (Extracted from *Advanced Materials & Processes 4/94*)

Shape memory alloy system

A system in which a shape-memory alloy collar expands to break a restraining bolt to release spacecraft solar panels has replaced explosive bolts on a recently launched spacecraft, according to TiNi Alloy Co. The device, called Frangibolt, is composed of a specially notched bolt and a cylindrical actuator made of Nitinol, a nickel-titanium shape-memory alloy. An external element heats the actuator, causing it to expand and break the bolt at the notch.

According to the company, a Nitinol actuator that is 2.5 cm long having a cross-sectional area of 6.5 cm^2 can exert 222kN through a displacement of as much as 1.3 mm. Unlike bolts that are separated by explosive devices, Frangibolts can be stored and shipped without special safety precautions, are easily installed, and produce no gas.

particles, or high shock loads that can damage sensitive spacecraft instruments.

For more information, contact: TiNi Alloy Co., 1621 Neptune Dr., San Leandro CA 94577, USA. (Extracted from *Advanced Materials & Processes 4/94*)

Fly ash and recycled aluminium form new alloy

Researchers have said that they have found that the properties of solid metal castings can be replicated by mixing fly ash from coal combustion with aluminium alloys. The new composite is known as Ashalloy and was developed by the University of Wisconsin in cooperation with the Electric Power Research Institute (EPRI).

EPRI estimates that of the 90 million tons of coal combustion by-products generated annually, only 25 per cent is currently used, much of it as extenders in cement and in polymers. The remainder ends up in landfill or surface impoundments.

One benefit from Ashalloy is metal cost savings. The composite consists of up to 20 per cent fly ash and 80 per cent recycled aluminium. It therefore obviates the need for buying 20 per cent of the metal normally required for die casting alloys. The composite can work with primary or secondary aluminium. Research shows that extruded Ashalloy tops the standard cast composite in hardness and density; the data indicates that it has a significant advantage in material and energy costs over conventional alloys and metals.

Cast samples of Ashalloy were subjected to heat treatment and extrusion; they were then examined by electron microscopy and underwent physical and mechanical testing. The results were apparently encouraging. The heat treatment caused no debonding of the fly ash particles, but it actually increased the hardness of the composite.

Potential promising application areas are automotive components using standard foundry techniques. It could lower the cost of producing vehicles that are more aluminium intensive. In addition, engineering properties could be enhanced, such as engine blocks, abrasion resistance for braking systems and sound abatement in valve covers. Research continues to identify machine parts and components for prototype production. In order to make the programme commercially viable, processing techniques have to be achieved to yield specific alloy properties, property databases must be compiled and the recyclability of the alloys has to be specifically addressed. (Source: *American Metal Market, 10 May 1994*)

Alloys from Inco Alloys International Inc.

In the production of high-performance alloys, the critical first step of alloying requires sophisticated equipment, stringent controls, and expert knowledge. To meet customer's needs for alloys of precise compositions and microstructures, Inco Alloys International uses a variety of alloying facilities.

Air melting in electric-arc or induction furnaces is used for many alloys; sometimes for final alloying, but more often in conjunction with further refining by argon-oxygen decarburization (AOD).

Melting in air can result in impurities in some alloys, a problem eliminated by vacuum induction melting, which is used to produce ingots for direct rolling or for remelting.

Remelting is done by two methods, both with extremely precise, computerized control. Electroslag remelting uses electrical resistance heating to remelt an ingot (electrode) under molten slag containing fluxes that remove impurities. Vacuum arc remelting refines the structure of cast electrodes in a contaminant-free chamber. Remelting yields alloys of the highest level of refinement for the most demanding applications.

The company produce a wide range of alloys, not all of which are for sale in all countries. These alloys are the following:

Inconel alloy 625: Major applications are bellows and expansion joints;

Inconel alloy 622: Particularly suited to acidified halide environments, especially those containing oxidizing acids;

Inconel alloy 686: Suited for aggressive environments, such as FGD systems, or process plants where resistance to localized corrosion is critical, or processes involving mixed acids;

Inconel alloy 725: Suitable for oil gas and marine engineering applications;

Inconel alloy 718SPF: Amenable to process technology previously restricted to aluminium and titanium, opening up a range of design opportunities for combining superplastic forming and high strength at high service temperatures;

Inconel alloy 783: Candidate material for a range of aerospace gas turbine engine applications, notably casings and rings, shrouds and seals for engine compressor and turbine stages, and for exhaust systems;

Incoloy alloy 925: Developed for use in gas production applications, such as tubular products, tool joints, and equipment for surface and downhole hardware;

Inco alloy 25-6MO: Applications include equipment for handling sulphuric and phosphoric acids, offshore platforms and other marine equipment, and bleaching circuits in pulp and paper plants.

For further information, contact: Inco Alloys International Inc., Huntington, WV 25720 USA. (Extracted from *Advanced Materials & Processes 1/95*)

Special bars from Copperweld

Copperweld Steel Co., is an integrated electric furnace steel mill with ladle refining, vacuum degassing, bottom pouring, two rolling mills, complete thermal treatment facilities, and turn-and-grind operations. The company produces alloy steel bars for steel service centres, forgers, automotive suppliers, industrial and machinery manufacturers, and mining- and energy-related industries. Specialty products developed and produced by the company includes: Aqu-Bar, Excalibur, Velvabar, and Multi-Tech 2000.

Aqu-Bar is particularly suited for machining and hot, cold, or warm forging applications where close tolerances and size consistency are important. Velvabar has a bright, smooth, scale-free finish requiring less machining by the customer; it holds closer tolerances than hot-rolled steel, and has more precise straightness.

Excalibur was developed particularly for machining with carbide tooling. It is a fine-grained, calcium-treated alloy steel that helps tools last longer and promotes better chip breakage.

Multi-Tech 2000 was developed through the optimized addition of tellurium, which improves cold formability and machinability by changing the morphology of sulphide inclusions. Normally, such inclusions are long and stringy, which results in anisotropic properties in cold-rolled products. However, tellurium-treated steel has elliptical inclusions, which improve isotropic properties and can be beneficial in many applications.

For more information, contact: Copperweld Steel Co., 4000 Mahoning Ave. N.W., Warren OH 44483, USA. (Extracted from *Advanced Materials & Processes 1/94*)

6. MATERIALS PROCESSING

Precipitation-hardening alloys

Designers of stainless steel and nickel alloy products are routinely faced with making tradeoffs between the properties needed for manufacturing and those required for its end use. When such compromises begin to adversely impact cost of performance, precipitation hardening (PH) alloys may offer a solution. Good candidates are strip and wire components that must be extensively formed or drawn during manufacturing, then must exhibit high strength and toughness in service.

PH alloys are similar to other stainless steel and nickel-base alloys, with one major exception: they contain small additions of copper, aluminium, phosphorus, or titanium. After a part made of a PH alloy has been formed, it is given an age-hardening treatment in which these elements precipitate as hard intermetallic compounds that significantly increase hardness and strength.

Despite their more complex metallurgy, PH alloys are not necessarily more costly than many non-age-hardenable alloys. In fact, performance may be substantially higher than such alloys, without a cost penalty. Although corrosion resistance is decreased (or possibly increased) during the aging cycle, it is only by a slight amount.

PH stainless steels are available in one of two conditions: annealed (condition A), or tempered (condition C). The annealed alloys are relatively soft and formable. After forming, the parts can be age-hardened. Tempered alloys are passed through a rolling mill to impart an element of cold work, usually 60 per cent. From this condition, the alloys can be heat treated to exceptionally high hardness levels and yield strengths in the 1200 to 1790 MPa range. Condition C is the starting point for very high strength parts, but forming must be minimal and simple, with generous radii.

As might be expected, most users need more options. Condition A may be too soft as a starting point to heat treat the part to the strength required; and condition C may be too hard for forming. In such cases, a precision reroll mill may be of service.

Rerollers are specialty producers who stock cold- and hot-rolled stainless steel and nickel alloy strip in large quantities. They custom roll it to gauge and temper, heat treating it between passes to neutralize the effects of work hardening. By controlling the amount of cold working, they can achieve an intermediate temper, somewhere between conditions A and C.

Austenitic PH alloys are used in applications requiring high strength, moderate corrosion resistance, and good fabricability. Austenitic stainless steel grades require high aging temperatures, about 700° C. Their corrosion resistance is slightly decreased by heat treatment, but oxidation resistance remains very good.

Martensitic PH alloys are typical of very high chromium-content PH alloys. They can be heat treated at relatively low temperatures, and exhibit high strength and other beneficial mechanical properties in elevated-temperature service. They also exhibit dimensional stability during age hardening, making them ideal for formed parts that must meet tight tolerance specifications.

Semi-austenitic alloys are much more complex metallurgically than other stainless steels. They are austenitic in the annealed condition, and must be transformed into martensite in order to age harden.

Nickel alloys are used for many high-strength parts used in demanding environments. It can be age-hardened, however, ductility increases as strength levels diminish. It maintains both strength and ductility over a wide range of temperatures.

For all the above compositions, specific heat treatments are best selected from manufacturers' data, or standard industry specifications. When heat treating plays a significant role in engineering the part, the services of an outside heat treater experienced with aircraft or corrosion-resistant alloys might be needed.

Designers who are hesitant about entering the realm of metallurgy will discover that using precipitation hardening alloys is not as complicated as it might seem. Producers and distributors of these alloys are prepared to give assistance through selecting an alloy to the finished part. (Extracted from *Advanced Materials & Processes 12/95*)

Radial forging of superalloys

The goal of process modelling is to optimize existing processes, design new processes, and determine causes and or corrective actions for specific manufacturing problems.

Radial forging is an open-die process for converting ingots to billets, reducing billet cross-sections, and forging shafts, axles, and bar stock of round, square, and rectangular cross-sections. The proper choice of radial forging process parameters (workpiece temperature, workpiece length, axial feed rate, stroking rate, reduction per pass), has traditionally been governed by empiricism, trial and error, and operator experience. However, as requirements for aerospace materials become more stringent, analytical methods to predict process parameters become essential. Further, the radial forging process can be fully automated, which makes it a good candidate for such analytical methods.

The proprietary three-dimensional finite element model used at Teledyne Allvac (Monroe, N.C., USA), was developed by Colorado State University. It is apparently unique in that it approximates deformation as a steady-state process, implying that all particles following the same path through the forge are subjected to nearly the same thermal and deformation histories. This assumption is based on the observation that billet surface temperatures remain nearly constant, except at the very ends.

Steady-state analysis requires the definition of a suitable control volume fixed in time and space. In this case, the control volume is selected to conform to the shape of the billet just prior to being struck by the hammers. The control volume is further limited to the portion of the billet in the immediate vicinity of the forging box. The combination of the steady-state assumption and the relatively small control volume leads to an order of magnitude savings (hours as compared to days) in computer time compared with a transient (stroke-by-stroke) analysis of the entire billet.

The above assumptions also eliminate the need to deal with kinematic boundary conditions at the ends of the billet, which have often posed a problem in transient analyses. The model also assumes that elastic deformations are negligible compared with plastic deformations. As a result, the mechanical behaviour of the metal is modelled as a non-Newtonian fluid, in which stress is a nonlinear function of strain rate.

The entire forging operation consists of several passes through the forge, with progressive reductions in diameter. It is simulated by alternating steady-state thermomechanical analyses, which simulate forging, and transient thermal analyses, which simulate the cooling between passes. Because the deformation caused by hammer blows at the hammer billet interface is primarily radial, the friction at the hammer billet interface is considered to be sticking friction.

Workpiece data input to the code consists of mechanical properties, including flow stress, strain rate, and temperature; and thermophysical properties, including heat capacity and conductivity as a function of temperature. Process data include: furnace temperature, air temperature, feed rate, die geometry, die temperature, number of passes, and billet entry and exit diameters for each pass. User-specified empirical coefficients are used to model die chill, heat transfer to air (by convection and radiation), and deformation heating. Results calculated from the code include the temperature and strain profiles in the control volume during each pass, and a cumulative time-temperature history for different locations in the billet cross-section.

The code has been validated by matching surface temperature predictions to measured temperatures over many production runs for several alloys. In addition, specially designed experiments were conducted to develop data against which to further benchmark the code and calibrate empirical coefficients. In these experiments, infrared pyrometers mounted on the frame of the radial forging machine and connected to strip-chart recorders were used to generate a continuous readout of billet surface temperatures at the entrance and exit of the forging box. All events during forging were timed, beginning with the opening of the furnace door to transfer the billet from the furnace to the radial forging machine.

The code has been applied in designing radial forging practices for new alloys. For example, when a new crack-sensitive alloy was to be radially forged for the first time, the practice was first simulated with the model to verify that the temperature distribution in the billet would remain within acceptable limits during forging. The simulations indicated that the workpiece would overheat if the proposed practice were used. Suitable hold times were designed into the appropriate passes to compensate for this. The material was successfully forged based on the revised practice.

The code has also been very useful in refining existing practices for certain alloys. For example, in one alloy, the material coming out of the radial forging machine was found to have an acceptable microstructure. However, upon further processing by the customer, it was determined to be thermally unstable. This was attributed to the high internal temperatures developed during the radial forging process. The model was used to redesign the forging practice to lower the maximum internal temperature, and the thermal stability of the alloy has since been significantly improved. (Extracted from *Advanced Materials & Processes 10/95*)

Selective reinforcement of titanium investment castings

Manufacturers of aerospace components must respond to ever-increasing demands for improvements in mechanical properties such as elevated temperature tensile strength, stiffness, fatigue life, or resistance to impact damage. At the same time, they must maintain or reduce part weight. Titanium-matrix composites (TMCs) have the potential to meet the mechanical-property requirements of many advanced structural applications. However, they are often not cost-competitive to produce as near-net-shape parts.

The bicasting method of selectively reinforcing titanium investment castings with TMC inserts seems to overcome this constraint. It offers the advantage of obtaining strength and or stiffness benefits where they are needed, along with cost-effective utilization of expensive TMCs. The process is based substantially on conventional investment casting and TMC fabrication technology, and can be performed in existing production facilities.

There are four major steps in bicasting: (1) mould manufacture; (2) preform fabrication; (3) casting; and (4) post-casting processing and inspection. Investment casting moulds are conventionally made by coating a wax replica of the part (pattern) with multiple layers of a ceramic slurry. The pattern is subsequently melted out of the ceramic mould. TMC preforms are then placed within the mould cavity at the locations that are to be reinforced. Preform geometry, composition, and fabrication method can be tailored to the required mechanical property improvements. Except for modifications that permit preform placement, bicasting moulds are identical to conventional titanium investment casting moulds. The titanium alloy to be cast is prepared by vacuum arc remelting of consumable electrodes in water-cooled copper crucibles. During casting, the TMC preforms are surrounded by molten metal, which then solidifies, embedding them in the casting. The parts are then processed via conventional titanium practice, including chemical milling, hot isostatic pressing, weld repair, heat treating, and inspection. (Extracted from *Advanced Materials & Processes 4/94*)

Bandsaw for high-speed cutting

Amada Co. Ltd., has developed a bandsaw capable of high-speed cutting of titanium alloys, inconel, and other difficult to machine materials which are used in nuclear power plants and aerospace development.

A mechanism is adopted for working the bandsaw blade vertically, which minimizes the cutting machine vibrations and sawblade chipping. This is the first time that a genuine bandsaw has been developed using a cemented carbide blade for working with materials which are difficult to machine. In addition, the company plans to venture into the field of machining materials which are extra difficult to machine, which were previously cut primarily by whetstones. The CTB400 bandsaw is for cutting round and square materials with diameters up to 430 mm. It is operated automatically by CNC control. The optimum cutting depth and speed can be automatically set for each cutting operation.

To prevent chipping of the cemented carbide blade, the bandsaw vibration was suppressed to one-sixth of that of counterparts, by adopting a vertical construction. The machine is designed as a vertical type and the vertical frame (saw driving and saw supporting system) are directly connected to the machine. Connecting the sawblade support directly to two linear guides fitted at the machine lower part has increased the stability. In addition, the number of parts on the machine bed was reduced, and the rigidity increased by using steel plates 16 mm thick. The end result of the new design and modifications is greatly reduced vibration. The vice for holding the material was separated into a front vice and rear vice to clamp the raw material and product accurately and to prevent sawblade chipping. Further, the use of independent vices enables the materials to be machined without loss.

Resulting from this, superheat-resistant alloys such as stellite and iconel, as well as titanium alloys and chilled cast iron can be cut with comparative ease. Chilled cast iron can be cut at double the speed compared with conventional types of bandsaws, materials resisting machining can be cut at the highest speed in the world, and the coarseness of the cut faces is reduced to one-fifth.

For more information, contact: Amada Co. Ltd., 200, Ishida, Isehara City, Kanagawa Pref. 259-11, Japan. (Source: *JETRO*, August 1995)

7. MATERIALS TESTING

Aerospace testing facility

For many years Howmet Corporation has been recognized as a leader in precision investment casting of sophisticated, high-temperature nickel, cobalt, and titanium alloys for flight and land-based gas-turbine engine applications. Many of the components that the company produces operate under extreme environmental conditions found in the hot section of the gas turbine engine. The temperature of the combustion gas entering the turbine can reach as high as 1480° C, and it is critical that the parts operating in the turbine section maintain their properties throughout their designed life.

Most nickel-base alloys used for advanced flight engines typically contain 15 to 20 elements that are controlled to concentrations as low as a few parts per million. Highly reactive elements such as hafnium, yttrium, and rhenium may be included. The high integrity of the final product is totally dependent on the quality controls imposed on the raw materials and manufacturing methods used throughout its processing history.

A key element in maintaining the high quality standards of all materials in the manufacturing process is the analytical and testing laboratory. The Howmet Research Center laboratories have the following capabilities:

Analytical chemistry: analysis of metallic alloys and non-metallic materials.

Physical testing: thermal analysis, bulk property determination, and particle-size analysis of metallic and non-metallic materials such as ceramic powders, resins, and waxes.

Micro-analysis: metallography and image analysis for microstructural characterization.

Electron optics: scanning electron microscopy and electron microprobe analysis.

Mechanical testing: tensile, stress-rupture, creep-rupture, and axial low-cycle fatigue; and axial and component high-cycle fatigue testing of metallic materials. Limited testing of shell and core materials is also available.

Heat treatment: vacuum, partial pressure, argon, and air heat-treatment, including controlled gas fan cooling and oil or water quenching.

Together the laboratory facilities support a wide range of corporate analytical and testing needs. Incoming process materials are checked for conformity to internal specifications. Testing is also required as part of the process for metallurgical approval of the production casting process. The laboratories provide production support ranging from process problem-solving to failure analysis.

New materials and processes provide ongoing challenges to the laboratories. Examples of these new materials are the conventional and XD (Martin Marietta) titanium aluminides. The low intrinsic ductility of these alloys has forced improvements in axial alignment techniques during tensile and fatigue testing to assure valid measurements. New analytical standards for chemical analysis are also required. The recent installation of an automated stress and creep-rupture testing system, and a fully integrated heat-treatment system are expected to increase throughput, improve process control, and decrease operator supervision.

The analytical and testing laboratories provide a wide range of essential production support services to domestic and overseas manufacturing operations. The extensive laboratory capabilities are available to commercial customers to meet their routine, or special testing needs.

For more information, contact: Director, Quality and Technical Services, Howmet Research Center, 1500 South Warner Street, Whitehall, MI 49461, USA. (Extracted from *Advanced Materials & Processes* 2/95)

Non-destructive testing

The science of non-destructive testing (NDT) is assuming an increasingly important role in all types of manufacturing and engineering activity due to the proliferation of new materials and more demanding quality standards. Following significant investments in new technologies, Forbairt's National NDT Centre (Dublin, Ireland), is now positioned to offer industry a complete service in various methods of NDT, including total quality auditing and specialist consultancy.

The Centre houses some of the most advanced industrial ultrasonic scanning systems available: a state-of-the-art realtime radiographic facility; comprehensive magnetic particle, eddy currents and liquid penetrant equipment and a fibre-optic baroscope.

NDT involves the physical examination of materials or components without altering or compromising their structural integrity. It is used to detect variations in structure and the presence of cracks or other physical discontinuities in materials; to measure the thickness of coatings, variations in conductivity and disbonding in composite materials; and to establish the presence of foreign bodies in food products.

The National NDT Centre has performed consultancy work for clients in the heavy engineering, plastics, aerospace, electronics and food industries, to name a few. The Centre sees itself as a national resource, drawing on the expertise of a whole range of individuals from within Forbairt, in addition to that of its core personnel, in areas such as metallurgy, corrosion, coatings and mechanical testing. Consistent with its role as a national organization, the Centre represents Ireland on several international committees involved in drafting internationally harmonized standards for NDT testing.

The IS EN 473 scheme, which has emerged as the European Union (EU) standard for the certification of NDT personnel, is a centralized scheme requiring participating countries to appoint an independent certifying body. To operate the scheme, the Centre has applied for EN 45013 approval, which is a European accreditation standard for laboratories offering a certification scheme for personnel.

The Centre sees itself as a national centre servicing the NDT requirements of a broad range of industrial sectors. The Centre is there to provide standalone services and solutions to specific problems. As safety requirements become more demanding and as the quality of products continues to improve, the need for NDT is expanding, as is the technology required.

For more information, contact: The National Centre for Non-Destructive Testing, Forbairt, Glasnevin, Dublin, Ireland. (Source: *Lab-Tech*, 1995)

8. PUBLICATIONS

Principles of Heat Treating Plain Carbon and Alloy Steels
ISBN:0-87170-538-9. 1995. approx. 300 pages. ASM Order No. 498

This resource book helps in determining which steel and heat treatment process will best meet your needs. It reviews current methods, both quantitative and correlative, in determining hardness or strength. A brief review of the concepts behind the common method of graphically depicting decomposition of austenite and the time-temperature transformation diagram is provided. It also covers computer modelling of heat treatment processes.

***Woldman's Engineering Alloys*, 8th Edition**
ISBN: 0-87170-501-X. 1994. approx. 300 pages. ASM Order No. 476

Data on the latest alloy advances, with information on over 60,000 alloys from more than 1,650 companies in 22 countries is provided in this book. The listings include the chemical composition, selected properties, main uses, tensile and yield strengths, elongation, reduction in area, and hardness number.

***Worldwide Guide to Equivalent Nonferrous Metals and Alloys'*, 3rd Edition**
ISBN: 0-87170-540-0. 1995. 500 pages. ASM Order No. 502

This reference book aids in finding equivalents for a material specification or designation, providing valuable composition tables allowing comparison with similar alloys. The book is organized by material group or class and is further subdivided into groups and finally into individual alloys.

Fatigue Data Book: Light Structural Alloys
ISBN: 087170-507-9. 1994. 350 pages. ASM Order No. 493

This one volume consolidates fatigue data on aluminium, magnesium and titanium alloys. Over 500 tables and figures covering much of the known S-N fatigue information for common light structural alloys is provided. Sections included are: aluminium, magnesium and titanium alloys.

ASM Speciality Handbook Aluminium and Aluminium Alloys
ISBN: 0-87170-496-X. 1993. approx. 700 pages. ASM Order No. 450

This book is useful for those who select and process aluminium and aluminium alloys. Engineering technologies, including aluminium metal-matrix composites are combined with essential information on aluminium.

ASM Speciality Handbook Carbon and Alloy Steels
ISBN: 0-87170-5, 1995, approx. 680 pages. ASM Order No. 496

This book provides in-depth reviews of formability, weldability, machinability and hardenability of various steel grades. Articles on new applications for steel are included, including material requirements, applicable codes, standards and specifications.

Materials Properties Handbook: Titanium Alloys
ISBN: 0-87170-481-1. 1993. approx. 800 pages. ASM Order No. 446

The comprehensive data sheets on more than 60 titanium alloys supply not only extensive graphical and tabular information on properties, but also describe, or illustrate important factors aiding in the selection of the proper alloy or heat treatment. This book includes the newest alloys made public, even those still under development.

ASM Handbook Volume 1: Properties and Selection: Irons, Steels, and High-Performance Alloys
ISBN: 087170-377-7. 1990. 1,063 pages. ASM Order No. MH10-1

This handbook contains the work of more than 80 authors and 120 peer reviewers. Sections include: cast irons, carbon and low-alloy steels, hardenability of such, fabrication characteristics, service characteristics, speciality steels and heat-resistant alloys, materials availability and recycling.

ASM Handbook Volume 2: Properties and Selection: Nonferrous Alloys & Special-Purpose Materials
ISBN: 087170-378-5. 1991. 1,328 pages. ASM Order No. MH10-2

This updated handbook contains new topics such as recycling, superconductors, metal-matrix composites, and intermetallics. Sections include: specific metals and alloys, special-purpose alloys, superconducting materials, pure metals, recycling and toxicity of metals.

ASM Handbook Volume 3: Alloy Phase Diagrams
ISBN: 087170-381-5. 1992. 512 pages. ASM Order No. MH10-3

This is probably the phase diagram reference for engineers containing 1,079 binary systems. The Binary Alloy Index lists all 2,970 systems including 835 with no diagrams, but all information as it exists.

All the above publications are available from:

American Technical Publishers Ltd.,
27/29 Knowl Piece Wilbury Way,
Hitchin, Herts., SG4 0SX,
United Kingdom.

Standards, References and Special Technical Publications for the Metals Industry

***Metals and Alloys in the Unified Numbering System*, 6th Edition**
ISBN: 1-56091-314-2. 1993. 400 pages. Order No. UNS6

This edition contains 200 new materials designations and 1,000 revised materials designations. It guides through the thicket of trade names and designation systems to the metal or alloy needed. Each Unified Number is followed by a description of the material, its chemical composition, and cross-reference specifications.

A 1994 update is also available.

Reference Radiographs for High-Strength, Copper-Base and Nickel-Copper Alloy Castings

These reference radiographs illustrate various types and degrees of discontinuities occurring in high-strength copper-base, nickel-copper and related types of alloys.
Reference Number: E272.

Volume 01.02 of Section 1 Iron and Steel Products: Ferrous Castings; Ferroalloys

ISBN: 0-8031-2273-X, 670 pages, 102 Standards

Over 100 standards, including 20 specifications setting forth the property requirements of steel castings for general applications, structural purposes, and high-temperature and low-temperature service. Around 20 specifications fix the requirements which must be met by various ferroalloys. Thirteen alloy casting specifications list the necessary qualities for castings made of nickel and chromium alloys. The 30 specifications for cast iron detail property requirements for grey iron castings, cast iron pipe and fittings, ductile iron castings, malleable iron castings, and white iron castings. A further 6 standards focus on radiographic examination of castings.

Volume 02.01 of Section 2 Nonferrous Metal Products: Copper and Copper Alloys

ISBN:0-8031-2280-2, 888 pages, 169 Standards

Features 169 standards, including 75 specifications that set out the requirements for copper and copper alloy plate, sheet, strip, rolled bar, rod, bar, and shapes. A further 45 specifications set out the property requirements for seamless and welded tubes for ordinary use, water service, condensers, and special uses.

Volume 02.02 of Section 2 Nonferrous Metal Products: Aluminium and Magnesium Alloys

ISBN: 0-8031-2281-0, 788 pages, 78 Standards

Over 700 pages of the latest standards for aluminium and magnesium alloys. The specifications define the necessary qualities of aluminium, aluminium alloys and aluminium-covered steel.

Volume 02.04 of Section 2 Nonferrous Metal Products: Nonferrous Metals — Nickel, Cobalt, Lead, Tin, Zinc, Cadmium, Precious, Reactive, Refractory Metals and Alloys

ISBN:0-8031-2283-7, 810 pages, 172 Standards

Over 170 standards including 100 specifications for: castings; forgings; pipe and tube; plate, sheet and strip; rod, bar, and wire. It includes 70 specifications for: cadmium; copper; gold; hafnium; iridium; lead; lithium; palladium, platinum; rhodium; ruthenium; silver; tin; zinc; molybdenum; niobium; tantalum; titanium; and zirconium.

All publications in this section are available from:

ASTM European Office,
27/29 Knowl Piece Wilbury Way,
Hitchin, Herts., SG4 0SX,
United Kingdom.

Product and publications information

Tantalum/niobium Compounds: The company is a producer of these compounds primarily used in electroceramics, optical applications, cemented carbides, superalloys, catalysts and pigments.

H.C. Starck Inc., 45 Industrial Place, Newton, MA 02161-1951, USA

Hardfacing Alloys: This company offers a full range of wear-resistant products and services, including nickel and cobalt hardfacing alloys: powder, rod, casting, and ingot; thermal spray equipment; training and technical assistance.

Wall Colmonoy Corp. 30261 Stephenson Highway, Madison Heights, MI 48071, USA.

Materials Characterization: A wide range of materials surface analysis services for failure analysis, product/process improvement is offered using various techniques.

Surfaces Research & Applications Inc., 8330 Melrose Drive, Lenexa, KS 66214, USA

Comprehensive Metals Testing: A brochure details the company's extensive metals testing capabilities including in-depth dimensional inspections on internally and externally threaded fasteners, chemical analyses, microexaminations, and mechanical and NDT testing services.

Laboratory Testing Inc., P.O. Box 249, Dublin PA 18917, USA

Exotic Materials Components: A brochure including all types of exotic materials readily available. Available materials include: tungsten, molybdenum, titanium, tantalum, zirconium, cobalt and nickel alloys. Products include both corrosion and heat resistant materials.

Regal Industries Inc., 34900 Chardon Road #200, Willoughby Hills, OH 44094, USA.

Materials Engineering Journal: The *Journal of Materials Engineering and Performance* publishes contributions on all aspects of materials selection, design, characterization, processing, and performance testing. Scope includes all materials used in engineering applications. Published bi-monthly.

ASM International, Materials Park, OH 44073-0002, USA

Metals Handbook, Desk Edition: This volume combines the most-used information in the ASM's Metals Handbooks. It contains the knowledge a materials engineer needs all the time.

SEE ASM International, Materials Park, OH 44073-0002, USA

Stainless Steels, Nickel Alloys: A brochure covering a diverse line of precision rolled stainless steel, nickel, cobalt, and titanium alloy strip and wire, including detailed chemistries of more than 50 alloys.

Ulbrich Stainless Steels & Special Metals, 57 Dodge Ave., North Haven, CT 06473, USA

Most Requested Bibliographies: The *Search-in-Print '94* list presents a newly updated collection of the topics that generate the most interest. Produced on demand from international databases providing full details of each item.

Materials Information, ASM International, Materials Park, OH 44073, USA

NDT Training: Arc welding inspection and quality control training in all major NDT methods. Either on site, or at requesters home base.

Hobart Institute of Welding Technology, 400 Trade Square E., Troy, OH 45373, USA

Measuring Magnetic Properties: The company provide a magnetic materials measurement service to serve industrial engineering laboratories and materials producers.

LDJ Inc., MMS Department, 1280 E. Big Beaver Road, Troy, MI 48083, USA.

Trace-elementAnalysis: The company offers comprehensive elemental analyses capabilities, having experience with metals, alloys, rare-earth oxides, high-purity and electronic materials, sputter targets, and ceramics.

Shiva Technologies Inc., 6260 S. Bay Road, Cicero, NY 13039, USA

Mechanical Testing, Research: The company provide full machining capabilities and state-of-the-art equipment providing advanced, reliable testing of all types of metals, alloys, and composites.

Westsmoreland Mechanical Testing & Research Inc., P.O. Box 388, Youngstown, PA 15696-0388, USA

Computer-based Instruments: A catalogue of hard- and software for computer-based instruments. Features all main operating systems.

National Instruments, 6504 Bridge Point Parkway, Austin, TX 78730, USA.

Hand-held NDT Instruments: The company introduce their new line of hand-held hardness, thickness, roughness, and vibration measuring instruments. Other products include instrumented and uninstrumented impact test systems, universal test systems, and rheology test systems.

GRC Instruments, 5383 Hollister Ave., Santa Barbara, CA 93111, USA.

Portable Alloy Analyzers: The company is a supplier of advanced equipment for metal detection, materials testing, and chemical analysis.

Metorex Inc., 860 Town Center Drive, Langhorne, PA 19047, USA

Reconstruct your UTM: Reconstruction of outdated Instron, or similar electromechanical testing machines, the performance is equivalent to OEM's modern systems. Mechanical component replacement is avoided by utilizing the rugged frame hardware. Computer control and data acquisition are standard features.

Measurements Technology Inc., 4240 Loch Highland Parkway, Roswell, GA 30075, USA

Mechanical Test Fixtures: The company designs and fabricates mechanical test fixtures for use in evaluating all types of materials.

Wyoming Test Fixtures Inc., 421 S. 19th St., Laramie, WY 82070, USA.

Materials Analysis Laboratory: The laboratory provides complete contract analytical services for measuring the physical characteristics of powders and solids.

Micromeritics, 1 Micromeritics Drive, Norcross, GA 30093, USA.

World Calendar: A meetings diary for the materials industry, issued quarterly, includes over 1,300 events in more than 50 countries. Each entry contains full details of the location, dates, title, and description of main topics, contact address, registration details and working language.

ASM International, Materials Information Dept., Materials Park, OH 44073, USA.

UNIDO NEWS

Establishment of the International Centre for Materials Evaluation Technology (ICMET) in Taejon, the Republic of Korea.

One of the latest achievements of the UNIDO programme in the area of new materials is the establishment of the International Centre for Materials Evaluation Technology (ICMET) on the premises of the Korea Research Institute of Standards and Science (KRISS) in Taejon, the Republic of Korea. The preparatory and pilot activities phase has just started and is planned to be run from 1996-1998. The following information about the mission, objectives, functions and the work programme of ICMET will give the opportunity to our readers to know more about this new institution which is planned to provide a framework for developing countries to cooperate in this vital area for materials science and engineering.

As stated in the Feasibility Study on the Establishment of an International Centre for Materials Evaluation Technology, "...It is also worldwide recognized that reliable methods of testing and evaluation of new and advanced materials are crucial for their successful development and efficient incorporation into competitive industrial products. The standardization of testing procedures is a key principle in materials science and engineering, vital for a wide range of industrial sectors and, thus, will have a major influence on economic and industrial competitiveness in the future. Since markets and their competitive and regulatory forces have become global, worldwide standards development and deployment are essential for survival of an enterprise, a sector of industry and the economy of any country and for being competitive in the international trade."

MISSION

The mission of the International Centre for Materials Evaluation Technology (ICMET) is to develop international guidelines, codes of practice, standards on testing and characterization for new materials which can be accepted across national boundaries. It is also to bridge the gap between research and development organizations, innovative enterprises and the market place within developing countries to stimulate the diffusion of new materials and processing technologies and their application in materials related sectors of industry.

OBJECTIVES AND FUNCTIONS

The objectives of the ICMET is to respond to demand from the developing countries for building-up/strengthening technological capabilities in testing and evaluation of new materials and to act as the focus point for promoting international cooperation in this field.

The ICMET is operating under auspices of the United Nations Industrial Development Organization (UNIDO) and will focus on the following functions:

(a) AWARENESS BUILDING:

Gather, monitor and disseminate information from both developing and developed countries in the field of testing and evaluation of new materials, including on-going work of important standards committees and standards issues.

(b) COOPERATIVE R&D:

Identify industrially important areas for developing or improving new materials evaluation and characterization techniques through cooperative R&D programmes. Generate validated and widely acceptable techniques which can form the basis for the development of regional and international standards. Intercomparisons of laboratories and development of key reference materials.

(c) ADVISORY SERVICES:

Help industry and R&D institutions in the developing countries build up/strengthen their technological capacity in the area of testing and evaluation of new materials. Deliver the service provided by a network of organizations and locally wherever possible.

(d) TRAINING:

Make a valuable and sought-after contribution by organizing training programmes which offer practical experience to participants in key and developing fields of materials characterization and evaluation. Provide the scientists and technologists access to state-of-the-art instrumentation and testing facilities which are relevant and important to industry. Place emphasis in seeking industrial views in the design of the courses and making them attractive to participants from industry in developing countries.

(e) PROMOTION:

Promote international/regional cooperation in the field of testing and characterization of new materials in order to eliminate barriers in international trade.

WORK PROGRAMME

ICMET will work in close cooperation with existing research and testing centres and institutions, especially in the Asia and Pacific region at the initial stage.

Taking into consideration the novel nature of the Centre and the complexities of arrangements for international collaboration, the task is planned to be tackled in two phases

(a) Preparatory and Pilot Activity Phase (1996-1998):

The initial three year work programme started in January 1996 and includes the following key activities:

(i) establishment of a Technical Advisory Group and holding three annual meetings to provide guidance for the ICMET, advise on the selection of work programmes and assist in formulating a long-term plan for the operational phase of the Centre;

(ii) creation of an international network of institutions and individuals dealing with materials evaluation issues in policy making agencies, professional societies, enterprises, R&D centres and universities;

(iii) design of appropriate database system and its networking with the existing information system in the area of materials testing and evaluation;

(iv) organization of and conducting workshops and training courses on specific issues and problems in the area of testing and characterization of new materials;

(v) formulation of and launching collaborative projects involving intercomparison and validation exercises to demonstrate the basis on which the future R&D programmes can be developed and supported;

(vi) further promotion of the concept and work programme of ICMET;

(vii) development and approval of a long-term work programme for the next operational phase of the ICMET project.

(b) Operational Phase (starting from 1999):

Based on the experience of the pilot activity phase, a fully fledged work programme for ICMET will be put into operation. This is expected to cover all important categories of new materials and an extensive range of activities related to the functions of the Centre. The long-term structure and administrative arrangements for ICMET will be completed and functioning.

FUNDING ARRANGEMENTS

The international dimension of the designed Centre and the need for its efficient management and innovative methods of work require a kind of pump priming fund which will help the nucleus to grow to a stable size and demonstrate the value of such a cooperative programme Once this is achieved, the Centre should be expected to raise sufficient additional amounts from other sources for carrying out its activities.

The Government of the Republic of Korea expressed its interest in hosting the Centre and made the decision to allocate initial funding to start the project. Funds for the Centre's programmes are currently being sought from a range of organizations. These include: international aid and development funding organizations, national government development programmes, non government aid organizations, organizations sponsoring research, private industry and industrial organizations.

The ICMET provides a unique opportunity for funding organizations to "leverage" scarce financial resources. Funding organizations can direct funds towards specific programmes. This ensures that a high ratio of programme funds are effectively applied for maximum benefits of the target communities. Appropriate management procedures ensure a high level of financial accountability.

The Centre also seeks to consolidate funds from a variety of sources to undertake programmes for the benefit of developing countries.

INVITATION TO PARTICIPATE

Opportunities now exist, at a number of levels, for participation in the realization of the ICMET concept.

(i) Government organizations, R&D centres and enterprises from both public and private sectors of industry, and funding agencies active in new materials design, development, production and application are invited to submit project proposals and suggestions for areas of cooperation.

(ii) Research, manufacturing, marketing, financing, aid and policy development organizations and trade organizations are invited to make general operational suggestions and specific project recommendations. Discussions focused on identifying joint project opportunities involving the ICMET are also welcome.

(iii) Relevant international organizations are invited to seek formal links with the ICMET. In this manner, as the proposal develops, their additions and participation can be considered from the start.

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Printed in Austria
ISSN 1020-2978

V.96-82957 May 1996 900