AEROSPACE AND SPACE MATERIALS

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Keywords: Alluminium alloys, titanium alloys, superalloys, ceramics

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Summary

Aerospace and space industry has traditionally been a pacemaker for development and introduction of new materials systems and production technologies. The key driving forces for materials development are weight reduction, application-specific performance improvement, and reduced costs. Application of advanced engineering materials has significant impact on both economical and ecological issues.

Polymer matrix composites combine high stiffness and strength with low density and are therefore widely used for lightweight structural applications. Aluminum alloys essentially cover cryogenic and moderate elevated temperature range applications. Fiber reinforcements are used where high stiffness and/or wear resistance are required. Titanium alloys are presently used in the temperature range up to 500–550 °C. Fiber reinforcement offers dramatically improved strength and creep resistance, while

titanium aluminides may well push the temperature limit another 200 °C. Superalloys are capable of service temperatures up to 1150 °C. Long-term application requires protective coatings against hot corrosion and oxidation. Thermal barrier coatings have been introduced to further expand the useful temperature range of highly loaded components. Ceramics have only seen limited usage so far, but improvement of damage tolerance by fiber reinforcement will presumably broaden their application range at temperatures beyond 1100 °C in the future.

1. Introduction

The aerospace and space sector has traditionally been a promoter for the development and application of advanced engineering materials. The demand for these materials is generally spurred by the performance requirements of a component, which is usually an integral part of a complex technical system. The key issues to be addressed by advanced material development are material properties, material fabrication and finally costs. Component performance in this sector is primarily determined by mechanical properties such as strength, stiffness, and damage tolerance as well as by physical and chemical properties such as density, corrosion resistance at ambient and high temperatures. The availability of suitable fabrication methods plays a crucial role with regard to both material properties and costs and may therefore finally determine whether an advanced material will find application. Recently life cycle costing has been recognized as an important tool to assess the economic viability of the material.

The key driving forces for engineering materials development in the aerospace and space industry are weight reduction and increased temperature capability. Weight reduction is most effectively done by reducing density. Furthermore, weight reduction of an individual component can generate a snowball effect if, for example, the airframe and the engine of an aircraft are re-optimized allowing the use of less stringers, a down-sized engine, a smaller wing, etc. As a rule of thumb, each pound of direct weight saved in a primary structure results in nearly another pound saved indirectly in another part of the aircraft. A reduced take-off weight of an aircraft, space vehicle or satellite directly affects the amount of fuel burned, indicating the enormous economical and ecological benefits associated with lightweight design. For aircraft, similar benefits associated with a reduction of fuel consumption are achieved by increasing the efficiency of the engines via higher turbine inlet temperatures.

Although a number of additional criteria is stressed for each individual application, materials are often classified by using property charts such as shown in Figure 1. Considering their strength and density (Figure 1a) it becomes quite obvious why aluminum and titanium alloys are the classical lightweight aerospace alloys.

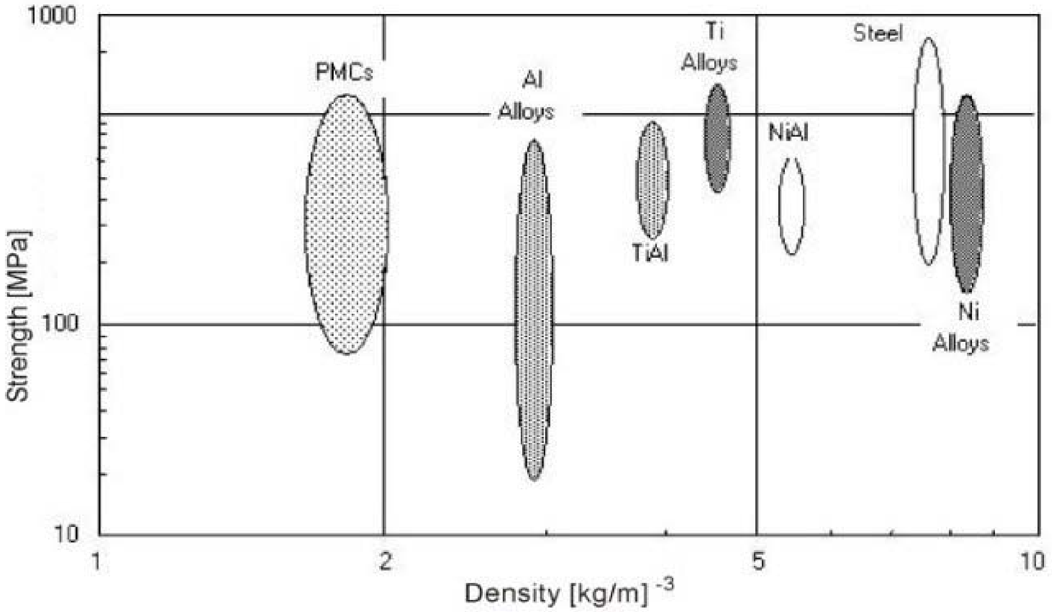

Figure 1a. Strength vs. Density Plot for Structural Materials

Aluminum alloys are used at room temperature and in cryogenic applications, and research has focused on further reducing the density, improving the elevated temperature capabilities and the corrosion resistance of these alloys. Polymer matrix composites offer even higher strength at lower density and have, to some extent, replaced classical metallic materials in specific applications. Titanium alloys are used where lighter aluminum alloys no longer meet strength, corrosion resistance and elevated temperature requirements. A major effort has been to increase the service temperatures of titanium alloys. Near-α type alloys with improved elevated temperature capabilities have been introduced and even more promising are titanium aluminides. With use temperatures of the order of 800 °C (Figure 1) these intermetallics have the potential to partly replace Ni-base superalloys. Ni-base superalloys are the prime choice materials in aeroengines, in an environment where high temperature capability and high strength are required (Figure 1b). Single-crystal turbine blades represent today's state-of-the-art technology. Despite their potential for high temperature applications, ceramic components have not yet been introduced into modern aeroengine design to a large extent, but the future may see an increasing number of ceramics for structural parts, especially when reinforced to enhance toughness.

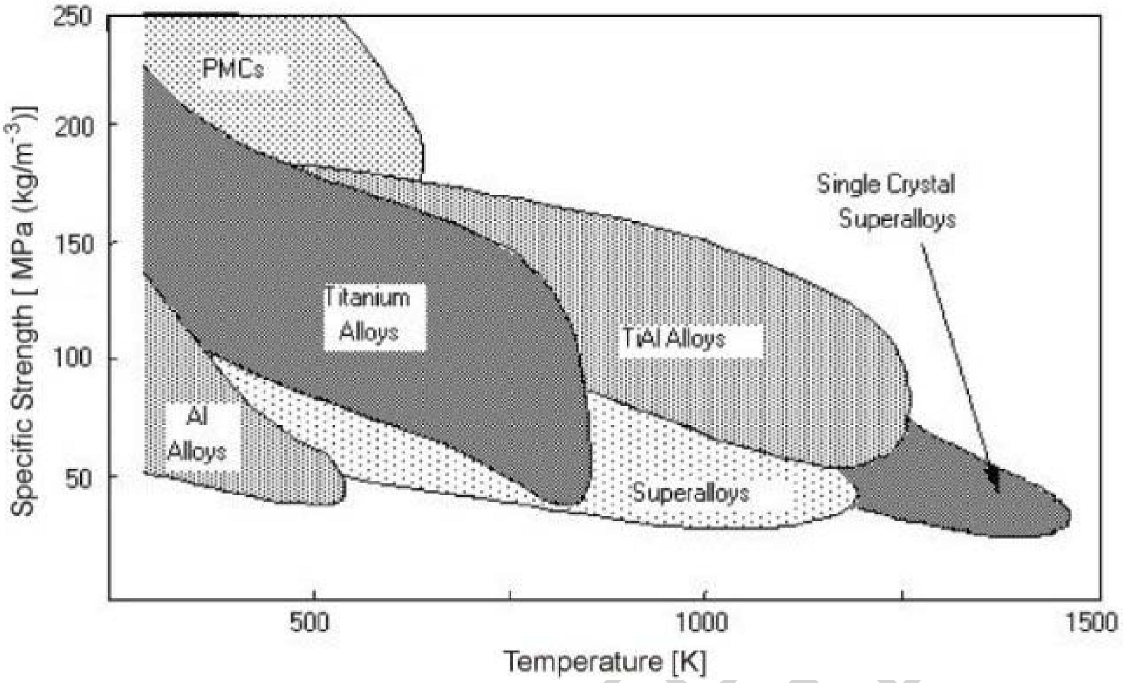

Figure 1b. Specific Strength vs. Temperature for Structural Materials

In general, materials properties can be tailored to the anticipated component application by modification of their chemistries and by manipulation of the processing. From Mother nature, materials scientists have adopted a third approach, the homogeneous, local or directional reinforcement of a component in order to improve properties like stiffness, strength, or toughness. Composites based on polymeric, metallic, and ceramic matrices are becoming increasingly important as aerospace and space materials.

Finally, for many applications, the demands placed on a component cannot be achieved by a single material, but require a materials system where parts of the system fulfil different tasks. A prominent example of such a system is ceramic thermal barrier coatings on superalloys in aeroengines. Obviously, improvement of these advanced materials requires a systems approach including the substrate, i.e., the superalloy, and the protective coating that usually comprises a multilayer system.

The following article will briefly cover achievements and development trends of monolithic materials —aluminum, titanium, nickel alloys, and ceramics—and composite materials with special emphasis on aerospace and space applications.

2. Aluminum Alloys

Over 70% of the structural weight of modern civil aircraft, like the Airbus A330/A340, or the Boeing 777, is attributable to high strength aluminum alloys. Most visible parts are the fuselage and the wings. The challenge from carbon fiber reinforced plastics not only led to the development of new alloys and processing techniques, such as aluminum-lithium alloys, powder metallurgical (PM) alloys or metal-matrix composites (MMC), but also stimulated the improvement of conventionally processed aluminum aerospace alloys as well as the introduction of near net shape technologies. New developments in the area of Al alloys are focused on either improving the performance of the material or reducing the cost of the final component. In most cases progress is judged by comparing the advances in performance with the properties of the two most dominant aerospace variants, the damage-tolerant Al-Cu base alloy 2024 and the high strength Al-Zn-Mg-Cu-base alloy 7075. Table 1 summarizes common aerospace aluminum alloys.

Alloy	**Chemical Composition (wt%)**	**Comment**
2014	Al-4.4Cu-0.7Mg-0.7Si-0.6Mn	medium strength
2024	Al-4.4Cu-1.5Mg-0.6Mn	damage tolerant
2090	Al-2.7Cu-2.2Li-0.1Zr	high strength Al-Li alloy
2195	Al-4.0Cu-1.0Li-0.4Ag-0.5Mg-0.12Zr	weldable Al-Li alloy; low temperature
2219	Al-6.3Cu-0.3Mn-0.18Zr-0.1V-0.06Ti	weldable; low & elevated temperature
2618	Al-2.3Cu-1.6Mg-1.1Ni-1.1Fe-0.2Si-0.1Ti	elevated temperature
6013	Al-1Mg-0.8Si-0.8Cu-0.5Mn	corrosion resistant
7010	Al-6.3Zn-2.5Mg-1.8Cu-0.13Zr	high strength
7050	Al-6.2Zn-2.2Mg-2.3Cu-0.12Zr	high strength
7055	Al-8.1Zn-2.3Cu-2.05Mg	high strength
7075	Al-5.7Zn-2.3Mg-1.5Cu-0.2Cr	high strength, tough
8009	Al-8.5Fe-2.4Si-1.3V	elevated temperature (RSR)
8019	Al-8Fe-4Ce	elevated temperature (RSR)
8090	Al-2.4Li-1.3Cu-0.9Mg-0.1Zr	damage tolerant Al-Li alloy

Table 1. Aerospace Aluminum Alloys

2.1. Engineering Properties

Lithium is the chemical alloying element which most effectively reduces the *density* of Al alloys. Al-Li alloys, with as little as 2 to 3 wt% lithium reduce the weight by about 10%—if stiffness increase is considered, then the effective weight reduction is 15%. The significant potential for weight savings has promoted the development of a series of advanced Al-Li alloys. Early enthusiasm of aircraft designers to replace large portions of conventional aluminum airframe structure by Al-Li alloys has made way for a more realistic assessment. The higher price of the lithium-containing alloys has turned out to be a major hurdle as have been unresolved technical problems, such as undesirable crack deviation and thermal instability. Modification of composition and processing routes, particularly to vary microstructure and texture, is thought to overcome this problem. So the future will see new Li-containing alloys with uncommon alloying elements like Ag or Sc.

In the late 1970s higher *strength* versions of 2024 were required for the Boeing 757/767 aircraft without sacrificing other properties. 2224 and 2324 with lower Fe and Si contents reduced the number of constituent particles and extra thermomechanical treatments maintained the toughness at the increased strength level. Higher strength versions of 7075 led to slightly modified alloys 7050 and 7010. Again, reduced impurity levels and small amounts of Zr assured high toughness. Further developments to improve strength and corrosion resistance resulted in the newer variants 7150 and 7055, respectively. Apart from conventional ingot metallurgy rapidly solidified aluminum alloys have the potential for ultra-high strength as demonstrated on a series of Al-9Zn-3Mg-1.5Cu base alloys. Fine dispersoids and an ultra-fine grain size lead to yield strength values greater than 800 MPa, however, at the expense of ductility and toughness. A similar base composition PM alloy—X7093— shows increased toughness at lower strength levels.

The main driving force for improving the *high temperature capabilities* of aluminum alloys is replacement of much heavier Ti alloys or even steels. Today the service temperature of conventional alloys like 2219 or 2618 is limited to about 150 °C, but advanced dispersion strengthened alloys such as 8009 or 8019 are aiming at temperatures as high as 450 °C. These alloys contain transition elements like Fe, Mn, Cr, Ni or Co as well as the rare earth element Ce, all of which have very limited solubility in aluminum. Therefore rapid solidification techniques or mechanical alloying are essential to produce a homogeneous, fine distribution of very stable dispersoids, which represent major obstacles to dislocation motion and thus improve strength and creep behavior. Extensive application of these alloys is limited due to cost-intensive production routes as well as poor ductility and toughness.

For high strength aluminum alloys often strength, stiffness and toughness increase with fall in temperature. Examples of *low-temperature applications* are aircraft operating at heights above 12 km (220 K), structures in space (120 K), storage of liquid cryogenic fuels such as oxygen (100 K) or hydrogen (20 K) for propulsion of launch systems such as Ariane or the Space Shuttle. Currently, the biggest cryogenic aluminum structure is the expendable tank for the Space Shuttle (Figure 2). It is made of the lithium containing Al alloy 2195, known for its improved low-temperature properties and superior strength-toughness combination, lower density and higher stiffness, resulting in weight savings of 4% compared with conventional aerospace aluminum alloy. Since riveted structures are not leak proof, tanks have to be welded. Welding of Al alloys has become a central issue and the establishment of friction stir welding has allowed a substantially increased number of Al alloys to be welded.

Figure 2. The External Boosters of the US Space Shuttle are made from Weldable Al-alloys(courtesy NASA, US)

The *corrosion behavior* of Al alloys is strongly influenced by the chemical composition, which effects their electrochemical potential, and the distribution of the various phases within the microstructure. Structure-dependent forms of corrosion such as intergranular attack, exfoliation and stress corrosion cracking (SCC) were encountered with heat treatable, high strength alloys, preventing exploitation of potential maximum strength of wrought products. New metallurgical processes and compositional modifications resulted in improved corrosion resistance. For copper bearing 7XXX series alloys, exfoliation corrosion and SCC behavior could be significantly improved by duplex aging, however, at the sacrifice of strength. Recently optimized heat treatment procedures have been developed that provide an optimum combination of strength and corrosion characteristics.

2.2. Cost-effective Processing

The need for cost and weight reduction of aerospace components has spurred the development of near-net shape technologies. For example, superplastic forming (SPF) allows sheet material to be deformed by 1000% and more when choosing the optimum combination of high temperature and slow strain rate. Combined with diffusion bonding SPF permits the manufacture of complex multilayer structures. A prerequisite for superplasticity is a fine grain size, which is stable during high temperature deformation. As a first step, new Al-Cu-base alloys particularly designed for superplasticity were developed. Additions of Zr to these alloys not only refine the cast structure but also lead to the formation of fine stable Al_3Zr precipitates that stabilize the grain structure. Refining the pan-cake shaped grain structure of conventional high strength Al alloys by recrystallization, as first demonstrated on 7075 by a four-step thermomechanical treatment, results in superplastic behavior with total elongation as high as 1200%.

Other activities in net-shape processing include advanced casting methods and new forging techniques. For example, the inner flap tracks of the Airbus A330/340 are produced by high performance investment casting, thereby substantially reducing the production costs. Incremental forging is primarily aimed at reducing tool costs and machining steps as well as the amount of material, which particularly pays off for more expensive material like Al-Li alloys.

3. Titanium Alloys and Aluminides

Probably no other metal is more closely associated with aerospace than titanium. With only about half the density of steels or superalloys, Ti alloys yield an excellent strength-to-weight ratio. Their corrosion resistance is excellent, their abundance essentially unlimited. However, the technology for ore reduction to metal is energy and cost intensive, and these are the prime reasons for their relatively high price. Despite strong efforts to increase the general industrial market share most of the titanium produced still goes into aerospace.

Over the years, the percentage of titanium parts in commercial aircraft structures has increased up to 10 wt%. Typical airframe applications are high strength forgings for critical components like flap and slat tracks in wings, nacelles, engine pylons, spars, fuselage frames, tubing for hydraulic lines, fasteners, rivets, springs and beams or undercarriage parts. But most of the Ti alloys go into the engine. Today they represent one third of the weight of modern aeroengines. First applications date back to the 1950s when Ti alloys paved the way for the first fan-type gas turbine engines. The large front fan of modern high-by-pass engines as well as most of the stator and rotor blades and discs of the compressor with temperatures approaching 530 °C are made of Ti alloys, but also less critical components like compressor casings, fan frames, bearing housings or ducts and vanes.

3.1. Microstructures and Mechanical Properties of Titanium Alloys

Usually Ti alloys are classified as near–α, $\alpha + \beta$, and metastable β alloys according to their structure which depends on the predominant alloying elements, of which aluminum is by far the most important (Table 2). Not only has aluminum a high solubility in titanium and thus a large strengthening capability but with only about half the density of titanium it also substantially reduces the specific weight.

The mechanical behavior of Ti alloys is mainly determined by their chemical composition and microstructure. The chemical composition primarily decides on the volume fractions of the α- and β-phase. Due to the limited number of slip systems of its hexagonal close-packed crystal structure, the α-phase is less ductile and more difficult to deform than the body centered cubic β-phase. Furthermore the Ti self-diffusion coefficient of α is about two orders of magnitude lower than that of β. Thus increasing the amount of aluminum, the most potent α stabilizer, effectively improves creep and oxidation resistance of Ti alloys while, unfortunately simultaneously leading to reduced ductility and formability; β-stabilizing elements like Mo, V, Nb reverse these trends.

The microstructures of Ti alloys are a result of thermomechanical treatments, which can roughly be separated into three processing steps: deformation, solution heat treatment and aging. Lamellar structures are established by cooling from the high temperature β-phase field, while equiaxed structures are a result of a recrystallization process. Solution heat treatment close to the β transus temperature leads to bimodal structures, consisting of equiaxed primary α in a lamellar $\alpha + \beta$ matrix. The various microstructures substantially influence mechanical behavior. Equiaxed structures generally have high strength, ductility, and fatigue strength, as well as a potential for superplasticity, while lamellar structures are more creep and fatigue crack growth resistant and have higher toughness. Bimodal structures such as found in Ti-6Al-4V—by far the most widely used titanium alloy—show a well-balanced set of engineering properties. Already developed in the 1950s, Ti-6Al-4V today represents more than 50% of all Ti alloys shipped and is thus considered to be the workhorse of the titanium industry. Other α + β alloys have only found limited application.

For elevated temperature applications near-α alloys are preferred, mainly due to good creep and oxidation resistance of the α-phase. Compared to the classical α + β alloy Ti-6Al-4V, they contain less β stabilizing elements, which increases the volume fraction of hexagonal close packed α-phase at the expense of body centered cubic β. In the hexagonal structure, diffusion is much slower and deformation more difficult, thus explaining the elevated temperature capability of near-α Ti alloys. Most near-α alloys also contain small additions of silicon to improve creep resistance, while small amounts of β add to strength as well as ductility. Over 40 years of alloy development have increased the upper service temperature of titanium alloys from about 300 °C to close to 600 °C.

Metastable β alloys are so rich in β stabilizers that the β-phase can be completely retained at room temperature. Due to the cubic crystal structure, metastable β alloys can be processed at much lower temperatures than α + β alloys; in fact, some of them are developed for forming operations at room temperature. Metastable β alloys can be hardened to the highest strength levels obtained for titanium alloys and still exhibit high toughness. Their major drawbacks are increased density due to the high content of alloying elements like Mo, Ta, V or Nb, reduced ductility at peak strength levels and limited weldability due to segregation and hardening in the welded condition. There are efforts to develop metastable β alloys with improved oxidation resistance for elevated temperatures applications and also employing them as the matrix for fiber reinforced components.

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Biographical Sketches

Dr. Manfred Peters earned his Ph.D. in materials science at the University of Bochum, Germany, in 1980 before he stayed for two years as Research Associate at the Department of Metallurgical Engineering and Materials Science at Carnegie-Mellon University, Pittsburgh, PA, USA. In 1982 he joined the German Aerospace Center (DLR) in Köln, Germany where today he is deputy director of the Institute of Materials Research. Dr. Peters' work is primarily focussed on light weight aerospace materials and high temperature coatings. He is author and co-author of more than 180 publications, holds two patents and has edited three books.

Dr. Christoph Leyens earned his Ph.D. in materials science at Technical University of Aachen, Germany, in 1997. He then joined DLR's Institute of Materials Research as a research scientist. 1998 and 1999 he was on sabbatical at Oak Ridge National Laboratory, TN, USA, for one year and at Lawrence Berkeley National Laboratory, CA, USA, for six months. He is currently group leader light metal composites at DLR. Dr. Leyens' work is focussed on environmental effects on aerospace materials and high temperature coatings as well as on long fiber reinforced titanium matrix composites. He is author and co-author of more than 90 publications, holds two patents and has written and edited two books, respectively. Dr. Leyens' work has been honored by several national awards