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Progress in structural materials for aerospace systems☆

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Abstract

This paper examines the progress in aircraft and aircraft engines from the standpoint of the role that better materials and processing has played. Such progress includes the relatively recent transformation of the aircraft industry from purely performance driven products to products that are driven by customer value. It is demonstrated that advances in materials and processing technology and understanding has enabled much of the progress that has been made since the inception of manned, heavier than air flight. The recent constraints of cost, as determined by customer value, have changed the way new materials are introduced and these trends appear to be the new paradigm for the aircraft and aircraft engine industry.

While the focus of this paper is aircraft and aircraft engines, the broader focus is on the role of materials in creating lightweight structures. There are examples used in this paper that are relevant to automotive applications once they are adjusted for cost. This matter is briefly discussed at the end of the paper.

Keywords: Solidification; Aluminum alloys; Titanium alloys; Ni-base alloys; Mechanical properties

1. Introduction

In the 21st century the key characteristics of successful aerospace and automotive products are good customer value and minimal environmental impact. Value is most simply thought of as service received from a product for money paid, including both initial cost and cost of ownership. Here, ownership cost includes the cost of capital as well as the cost of fuel and maintenance. Historically, improved structural materials have been a major enabler of better (higher value) products. Half a century ago better was measured largely in terms of performance. Today “Better” includes additional metrics as already mentioned. When these metrics are disaggregated into detailed design requirements, materials are still a critical enabler, but the characteristics that lead to the choice of a material for a new product are more complex and the

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choices available to the designer are more numerous. In this paper we will attempt to describe, in qualitative terms, the evolution of structural materials for application in aerospace systems and automotive products and the role of materials in creating customer value. Environmental impact also has several associated dimensions, including emissions of the product, effluent created during product manufacture and disposal/recycling capability.

A recent trend in the transportation industry is to improve customer value through creation of products that incorporate advanced structural materials and benefit from new manufacturing technologies. The objective is to create value by improving performance, reducing ownership costs, extending the system life and reducing environmental impact. Improved performance, as determined by materials, typically translates into higher structural efficiency, resulting in reduced product weight. Structural efficiency is the combined result of materials capability and design methodology. For example a stiffness limited component may incorporate a higher modulus material using the same design or it may use a new design that increases the section modulus or both. Honeycomb construction used in aircraft is an example of an increased section modulus design. The decision to introduce such a design impacts material selection because not all materials can be fabricated into honeycomb. Moreover, in recent years, honeycomb construction has fallen from favor because of the propensity for corrosion in the core when moisture is allowed to enter. This simple example illustrates the interaction between materials selection, manufacturability, design methods and ultimate product acceptance. Performance also must be normalized by damage tolerance because of the need for reliability. Improved reliability adds value through increased availability of the product to perform its intended function. Due to the increased number of design constraints driven by the growing number of product requirements and the greater range of structural materials now available, the designer is faced with complex choices for selecting a material to meet the requirements for a particular system. The outcome of competition between various classes of materials may also be associated with availability of the material in the appropriate product form, e.g. castings, forgings, rolled products and/or extrusions, and how amenable they are to net shape forming methods such as, superplastic forming, stretch aging, welding, casting and other manufacturing methods. These latter operations have historically been thought of as materials processing, but have seldom been treated as design constraints. While this characterization is still appropriate, it is no longer appropriate to treat processing as a separate consideration from materials selection.

Lightweight construction, consistent with meeting design intent, has become a universal requirement for all transportation systems but the complexity of current design and manufacturing methods now requires structural materials to satisfy a much wider variety of properties. This has led to many improvements in materials performance during the past few decades, which are mostly associated with an increase in our understanding of the relationships among composition, processing, microstructure and properties. This understanding has come from the technical literature, which provides guidelines for these relationships, and from industrial experiments, which provide detailed, but often empirical, information on how processing affects microstructure and properties. Integrating the information obtained from both sources has helped replace the ‘trial and error’ approach to alloy development and has reduced the time required to obtain the desired result. Further reductions are essential, however, because the product design cycle continues to get shorter and materials readiness at time of product launch becomes a “take it or leave it” opportunity window. We assert that the most obvious path to shortening the materials readiness cycle is through the development and use of more accurate and robust computational methods. These methods will, no doubt include both modeling and simulation. This is a major challenge for the materials community, but one that must be addressed and conquered if the continued contribution to competitive products attributable to materials is to be realized in future generation products.

2. Materials for aerospace systems

Since the first days of powered flight, aircraft designers have focused on achieving minimum weight, both in airframes and in propulsion systems. For example, the original Wright Flyer employed an engine with an aluminum block, which was virtually unheard of at the turn of the 20th century. From 1903 to about 1930 absolute minimum weight was necessary for practical flight, due in large part to the limited capability of the available propulsion systems. Consequently, the strength/weight ratio was the prime driver for materials selection for both engines and aircraft. While this consideration continues to be of first order importance, light weight is now necessary but not sufficient. Current design criteria are much more complicated, as mentioned in the Introduction, and winning products require new design methods as well as improved materials and processing methods.

The transition from internal combustion, piston engines to turbines represented a major "game changer" in aircraft. Beginning in the early 1940's with the German Messerschmitt Me-262 fighter aircraft, turbines became the preferred type of propulsion system. The performance of the early turbine engines was severely limited by materials capability, especially in terms of operating temperature. Jet powered fighters were in operation in the late 40's but large jet aircraft, e.g. bombers and transports did not become feasible until nearly a decade later, largely because of the increased difficulty of producing large turbine engines with adequate reliability. As will be described later, turbine technology has evolved and, today, propulsion technology is not the limiting factor it once was.

2.1. The evolution of aircraft and the role of materials

The evolution of aircraft that fly farther and faster has been a consistent goal of aircraft designers. Achieving this goal has required new materials with other attributes in addition to strength and light weight. For example, aircraft that fly at higher speeds require higher temperature capability materials due to frictional heating. As a consequence, skin materials have progressed from wood and fabric used in the early aircraft to advanced alloys of aluminum, titanium, and polymer matrix composites containing high-strength carbon fibers. Perhaps the most sophisticated aircraft ever built in the western world is the SR-71 Blackbird (Fig. 1) which had an all Ti alloy skin. This military aircraft was used for high altitude reconnaissance missions and was capable of speeds in excess of mach 3. The lessons learned from military operation of the SR-71 showed what practical limitations existed for commercial supersonic flight, especially above mach 2, where the skin temperatures exceed the capability of Al alloys. As a consequence, there has not yet been a large supersonic vehicle produced and entered into scheduled service that flies at these speeds. The Soviet Tupolev design bureau did produce several all-Ti Tu-144 aircraft but even in their economic system, it was not considered practical. The Concorde operates at mach 1.8 and is an Al airplane. Even so, it has not been economical to operate and is being retired from revenue service despite its technical success.

Damage tolerance became recognized as an important issue in 1954 when three Comet jet airplanes, manufactured with 7075-type aluminum, crashed [1]. The cause of the crashes was attributed to premature fatigue failure of the pressurized fuselage associated with stress concentrations at windows and hatches. Today, fracture toughness and fatigue crack growth have been incorporated as a primary design criterion in many products in

Fig. 1. Front view of the all titanium SR-71 Blackbird.

the same manner as strength was used 35 years ago. In fact, newer, higher toughness Al alloys for fuselage skins have enabled significant weight reductions through removal of some of the circumferential frames that serve, among other things, to arrest a running crack. This is discussed in detail later and is mentioned here as an example.

Beginning in the ‘80s, jet powered flight had become “a given” and other considerations for aircraft such as fuel costs, the revenue opportunities associated with increasing range and payload, and reducing landing weight fees again returned the technical focus to weight reduction but without sacrificing life. Then, in the ‘90s, the realization of the benefits of extending the life of the aging aircraft fleet resulted in a technical focus on improved damage tolerance and improved corrosion resistance. One response to this requirement was the possibility of retrofitting existing aircraft with newer and advanced alloys. This was done extensively in the case of the B-52 bomber and other military aircraft. In the case of commercial products, derivative aircraft models and the emergence of new, large twin engine aircraft was more representative of product trends.

The currently used airframe design methods have evolved over many years and the practices employed today incorporate both the benefit of this past experience and availability of better analytical methods. Static strength has been an important first order consideration since the beginning of flight and aircraft are usually designed to withstand a maximum operating load plus a safety factor, which is typically 1.5. In modern aircraft, static strength is necessary but not nearly sufficient, largely because of the protracted service lives expected of aircraft. The effect of fatigue on aircraft integrity began to be considered as long as 70 years ago. Design methods that consider fatigue as a constraint were introduced. Today, there are 2 conceptual approaches to calculating fatigue limited structural life: safe life and fail safe. Safe life design requires that no fatigue failure occurs in N lifetimes, where N always is greater than one and typically on the order of four. Safe life design was introduced in the 1930s and 1940s and relies strongly on detailed knowledge of service experience and requires rigorous product testing. Fail safe design was introduced in the 1950s and assures that catastrophic failure is not probable as the result of a failure of a single structural element. To achieve this result, fail-safe designs incorporate redundant crack pathways in the design. Finally, damage tolerance was introduced in the late 1960s and early 1970s, and couples crack growth analysis with periodic inspections to detect cracks and remove cracked load bearing members from service in situations where these would have a high probability of failure prior to the next scheduled inspection.

The material property requirements for use in airframes vary depending on the particular component under consideration [2]. The fuselage is a semi-monocoque structure that is made up of skin to carry cabin pressure (tension) and shear loads, longitudinal stringers or longerons to carry the longitudinal tension and compression loads due to bending, circumferential frames to maintain the fuselage shape and redistribute loads into the skin, and bulkheads to carry concentrated loads including those associated with pressurization of the fuselage. Strength, Young’s modulus, fatigue crack initiation resistance, fatigue crack growth rate, fracture toughness and corrosion resistance all are important, but fracture toughness is often the limiting design consideration. The wing is essentially a beam that is loaded in bending during flight. The wing supports both the static weight of the aircraft and any additional loads encountered in service due to maneuvering or turbulence. Additional wing loads also come from the landing gear during taxi, take-off and landing and from the leading and trailing edge the flaps and slats during that are deployed during take-off and landing to create additional low speed lift. The upper surface of the wing is primarily loaded in compression because of the upward bending moment during flight but can be loaded in tension while taxiing. The stresses on lower part of the wing are just the opposite. Compressive yield strength and modulus of elasticity in compression are the static material properties that influence design and, due to alternating loads caused during flight, fatigue resistance is also important. The tail of the airplane, also called the empennage, consists of a horizontal stabilizer, a vertical stabilizer or fin, and control surfaces e.g.

elevators and rudders. Structural design of both the horizontal and vertical stabilizers is essentially the same as for the wing. Both the upper and lower surfaces of the horizontal stabilizer are often critical in compression loading due to bending and, therefore, the modulus of elasticity in compression is the most important property.

Improved structural materials can contribute to improved performance and reduced operating costs for aircraft and spacecraft as noted in the schematic of Fig. 2. Since weight is probably the most significant contributor to performance and operating costs associated with fuel efficiency, the designer normally considers how a certain property will impact weight savings. In order to select the correct material for a component of a new system, aerospace companies have developed computer programs that perform trade-off studies. The properties of materials are placed in a database and comparisons are made between baseline materials and newer advanced materials for a particular component and failure modes as schematically illustrated in Fig. 3. By using this type of program a designer can determine the real potential weight savings. In addition, the cost of materials for weight reduction should not exceed the costs saved from reduced fuel burn, maintenance and landing fees [3]. Consequently, aerospace companies conduct a cost/benefit analysis for new candidate alloys. The total life-cycle cost consists of acquisition, operation and support costs [3]. The non-recurring development costs for design allowables,

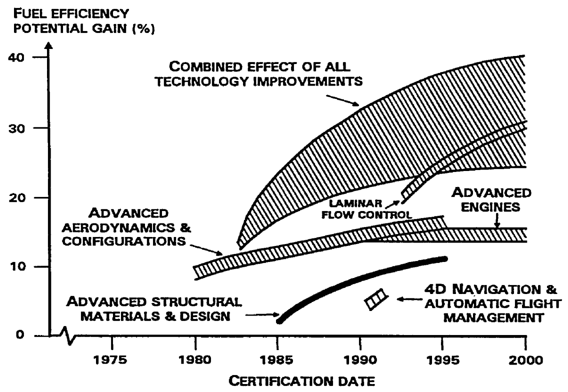

Fig. 2. Plot showing the relative contribution of various technology advances to improved fuel efficiency of aircraft.

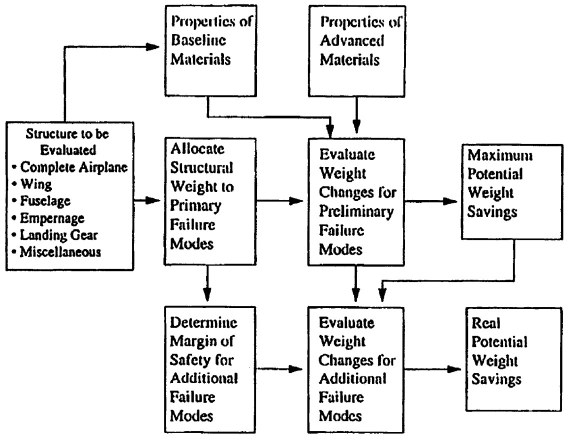

Fig. 3. Flow chart showing the order of events in computer aided materials selection.

etc., are typically divided by the number of airplanes to be built using the candidate material, and thus adds a fixed amount to the cost per pound saved [4].

2.1.1. Evolutionary improvement of aluminum alloys for aircraft

Improved structural materials are usually classified as either a revolutionary product, e.g. rapidly solidified and mechanically alloyed P/M alloys, discontinuous and continuous fiber reinforced metals and polymers, and structural laminates, or evolutionary, i.e. derivative alloys and tempers. Revolutionary products have had limited success in incorporation into aircraft due to cost of manufacture, qualification and certification and possibly modification of existing material production infrastructure. Although polymer matrix composites are being used in modern commercial aircraft, e.g. for the fin of the Airbus A310, the horizontal stabilizer of the Airbus A340 and the Boeing 777, aluminum alloys have remained the materials of choice for the airframe of most commercial aircraft. Evolutionary improved aluminum alloys have had a much more rapid insertion due to their lower manufacturing and/or life cycle costs, low substitution risk and the use of an existing material production infrastructure.

A summary of various microstructure/property relationships for aluminum alloys is given in Table

1. The basic metallurgical concepts for maximizing properties of age-hardenable aluminum alloys are well known [2,5]; the challenge is putting them into practice in alloy design. For example, the impurities Fe and Si form coarse constituents in 2XXX 7XXX, and 8XXX aluminum alloys and result in lower fracture toughness [2,6] and have an adverse effect on both fatigue crack initiation and fatigue crack growth resistance [7]. Coarse primary phases formed when solubility limits are exceeded at the solution heat treatment temperature (or those formed during processing and not re-dissolved during subsequent heat treatment) have a similar effect [8]. Consequently, low Fe and Si levels, a good knowledge of complex phase diagrams and tight controls on composition can be used to produce a good balance of strength, fracture toughness and fatigue crack growth resistance. As mentioned, the cost of implementing these concepts is often considered when selecting an alloy for a particular application, and the cost issue has often times delayed their implementation. Incremental improvement in yield strength of aluminum alloys is shown schematically in Fig. 4, in specific stiffness in Fig. 5.

The two major passenger aircraft manufacturers (Airbus and Boeing) have recently introduced aircraft, e.g. the Boeing 777 and the Airbus A340,

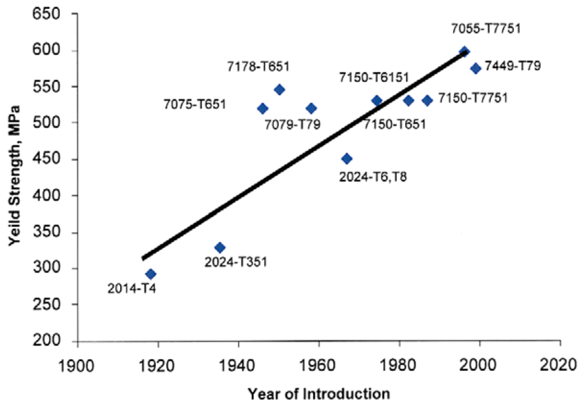

Fig. 4. Plot of yield strength for new Al alloys as a function of the year of introduction.

which utilized evolutionary improvements of older materials. The advanced materials on the Boeing 777 include a number of improved aluminum and titanium alloys and polymer matrix composites as well as laminates and lightweight sealants. Some examples of the aluminum alloys are shown in Fig. 6, and include 7150-T77 that has higher strength and damage tolerance when compared with 7050-T76, alloy 7055-T77 that has higher strength than 7150-T6 along with similar fracture toughness and fatigue crack growth resistance and alloy 2524-T3 that has approximately 15–20% improvement in

Table 1
Property-microstructure relationships in aluminum alloys

Property	Desired microstructural feature(s)	Function of feature(s)
Strength	Fine grain size with a uniform dispersion of small, hard particles	Inhibit dislocation motion
Ductility & toughness	Fine structure with clean grain boundaries and no large particle or shearable precipitates	Encourage plasticity and work hardening, inhibit void formation and growth
Creep resistance	Thermally stable particles within the matrix and on the grain boundaries	Inhibit grain boundary sliding and coarse microstructure
Fatigue crack initiation resistance	Fine grain size with no shearable particles and no surface defects	Prevent strain localization, stress concentrations, and surface slip steps
Fatigue crack propagation resistance	Large grain size with shearable particles and no anodic phases or hydrogen traps	Encourage crack closure, branching, deflection and slip reversibility
Pitting	No anodic phases	Prevent preferential dissolution of second phase particles
Stress corrosion cracking & hydrogen embrittlement	Hard particles and no anodic phases or interconnected hydrogen traps	Homogenize slip and prevent crack propagation due to anodic dissolution or HE

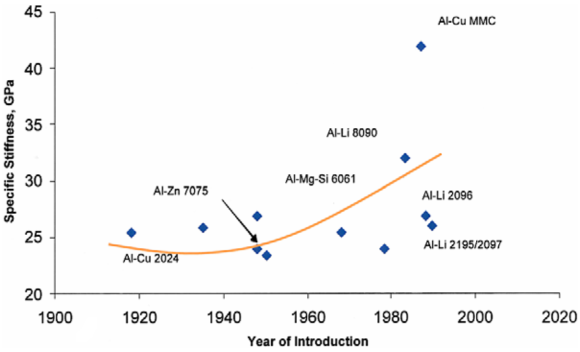

Fig. 5. Plot of the density normalized modulus of Al alloys as a function of the year of introduction.

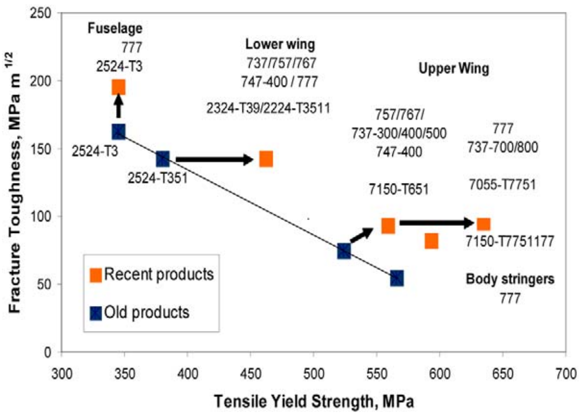

Fig. 6. Plot showing the improvements in strength-toughness combinations of some newer Al alloys.

fracture toughness and twice the fatigue crack growth resistance when compared with 2024-T3. The improved properties of 2524, compared with 2024 were obtained using the principles described in the previous paragraph. The higher toughness and greater resistance to fatigue crack growth of 2524-T3 helped in the elimination of tear straps in a weight-efficient manner on the Boeing 777. The T77 temper, developed by Alcoa, is based on a three step aging treatment that produces a higher strength with durability and damage tolerance characteristics matching or exceeding those of 7050-T76. The improved fracture toughness of 7150-T77 products is attributed to the controlled volume fraction of coarse intermetallics particles and unrecrystallized grain structure, while the combination of strength and corrosion characteristics is attributed to the size and spatial distribution and the copper content of the strengthening precipitates [2]. Phase diagrams and metallurgical simulators are currently being used to optimize compositions and fabrication schedules for a wide variety of aluminum alloys. Alloys 7449, used for upper wing skins, and alloy 7040, used for spars, were developed by Pechiney using this technology [9]. The relatively slow quench rate of thick plate was important in selecting the composition and low levels of Mg and Cu reduced heterogeneous precipitation significantly, ensuring good fracture toughness without sacrificing strength. The incremental improvements in usable damage tolerance are illustrated schematically in Fig. 7.

The 6XXX alloys have been considered to replace 2024 on a number of US Navy programs and alloy 6013 is being used on the Boeing 777. The major problems with 2XXX alloys for fuselage skins is that they must be clad since they can be susceptible to intergranular corrosion. In addition, the 2XXX alloys cannot be fusion welded, a process that is being considered for reducing weight and costs of manufacturing. The 6XXX alloys are weldable and cheaper than 2XXX alloys, however, Cu-rich 6XXX, e.g. 6013-T6 and 6056-T6 are also susceptible to intergranular corrosion. This susceptibility is associated with the formation of precipitate free zones at grain boundaries, which are developed during artificial aging, are depleted in Si and Cu and are anodic with respect to the grains [10]. A new temper has been developed, designated T78 that has a controlled

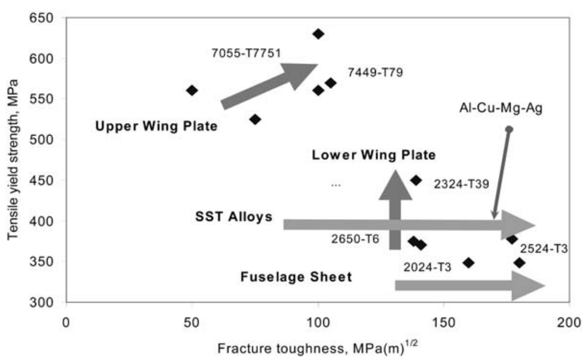

Fig. 7. Plot comparing yield strength-toughness improvements of 7000 and 2000 series Al alloys.

degree of overaging that desensitizes 6056 to intergranular corrosion, keeping the yield strength at an acceptable level with respect to the T6 temper. Other experimental tempers have been developed that prevent intergranular corrosion without any loss in strength [11]. An alternative to changing alloys to facilitate joining, is the use of a relatively new joining method known as friction stir welding (FSW). In this method, the alloys are not melted, but instead are joined in the solid state by mechanical working. In a sense, they simply are “kneaded together” with a rotating tool. The use of FSW creates the opportunity to join a wide range of Al alloys that cannot be fusion welded.

Superplastic forming is also a way to reduce part count and manufacturing cost since it lends itself to the manufacture of very complicated parts. For example, a single sheet can be formed into a complex arrangement of ribs and stiffeners and hence replace an assembly of parts and fasteners at a reduced manufacturing cost and at a reduced rate. Superplastic 7XXX alloys have been available for some time, however there have been difficulities with developing superplastic 6XXX alloys. A thermomechanical process has recently been developed for 6013-6011 alloys that produces a microstructure amenable to superplastic forming [12]. The process involves obtaining a fine, uniform distribution of one micron-sized particles for subsequent particle stimulated nucleation of recrystallization in order to obtain a fine (9.5 micron), equiaxed, recrystallized grain structure and a random texture. The alloys are then superplastic above 500 °C. Uniaxial tests indicated a strain rate of 0.5 at 540 °C and elongations of 375% using a stress of 4.7MPa.

2.1.2. Lighter weight, higher stiffness materials for aircraft

Aluminum-lithium alloys are attractive for aerospace applications because they have lower density and higher modulus than conventional aluminum aerospace alloys. Each weight percent of lithium lowers the density of aluminum by approximately 3% and increases the modulus by approximately 6%. The second generation of Al-Li alloys (the first being the Alcoa alloy 2020) was developed in the 1970s (alloy 1420 in Russia) and the 1980s (alloys 2090, 2091 and 8090). The Al-Mg-Li alloy 1420 and the Al-Li-Cu-X alloys 2090 and 8090 are now in service in the MIG 29 and the EH1 helicopter. Alloy 1420 has only moderate strength and the Al-Li-Cu alloys that contain approximately 2% lithium (2090, 2091 and 8090) have a number of technical problems, which include excessive anisotropy of mechanical properties, crack deviations, a low stress-corrosion threshold and less than desirable ductility and fracture toughness. Newer Al-Li alloys have been developed with lower lithium concentrations than 8090, 2090 and 2091. These alloys do not appear to suffer from the same technical problems.

The first of the newer generation Al-Li alloys was Weldalite 049® (2094) which can attain a yield strength as high as 700 MPa and an associated tensile elongation of 10%. A refinement of the original alloy, 2195, which has a lower copper content, is now being used for the U.S. Space Shuttle Super-Light Weight Tank. Alloy 2195 replaced 2219 and, along with a new structural design, enabled a 7500 pound weight reduction on the 60,000-pound tank. This allows an increased payload for the Shuttle and reduces the number of flights necessary for the construction of the International Space Station, thus saving millions of dollars. Three other recent derivatives of the third generation of Al-Li alloys are 2096, 2097 and 2197. They contain lower copper and slightly higher lithium content. Alloys 2097 and 2197 contain a very low Mg content to improve SCC resistance and Mn to prevent strain localization normally associated with the shearable Al_3Li present in the higher Li-containing alloys. Alloy 2097/2197 was recently selected to replace 2124, which had inadequate fatigue strength, for bulkheads on the F16. Alloy 2097 has a 5% density advantage over 2124 and at least three times better spectrum fatigue behavior or approximately 15% higher spectrum fatigue stress allowable. Although Al-Li alloys are more expensive than conventional aluminum alloys, the replacement of 2124 by 2097 for the BL 19 Longeron of the F16 doubles the service life of the part, saving over twenty-one million dollars for the 850 aircraft fleet operated by the USAF. Al-Li alloys, due to their better fatigue life, are also replacing engine access cover stiffeners, currently made from 2124. The Al-Li alloy 2098 has been successfully demonstrated/flight tested for F16 skins and has showed a 6X life improvement over 2024 skins.

There are a number of new aluminum materials that are being developed for use in commercial transport aircraft. Laminated hybrids of aluminum sheet with aramid-fiber-reinforced (ARALL) or glass-fiber-reinforced (GLARE) composites have high fatigue resistance and the potential for significant weight savings in aircraft. These materials also have resistance to burn through in the event of a fire and can potentially substitute for titanium in firewalls. On the negative side are the very high material costs, typically 7–10 times that of monolithic aluminum sheet. The cargo door of the C-17 is fabricated from ARALL. Laminates also offer the potential for adding extra functionality, e.g. load monitoring, damage detection, etc. Combining such functionality would make them more cost effective in aerospace structures. Other aluminum alloys under development include Al-Mg-Sc alloys. Although potentially very expensive because of the presence of scandium, they appear to have excellent corrosion resistance, and as a body skin they may not need to be clad or painted which would reduce maintenance costs. Higher-strength forgings, age-formable alloys, less-quench-sensitive alloys, and rivet alloys with improved formability are all being examined and developed for future use in subsonic aircraft.

Since a significant portion of airframe design is stiffness driven, there are opportunities for new metallic materials providing high specific stiffness relative to currently available materials. For example, aluminum beryllium alloys may provide an affordable sheet metal alternative to resin matrix composites in stiffness critical airframe structure. A comparison of the specific modulus and specific strength of AlBe (62%Be, 38%Al) with boron/epoxy, Ti, and Carbon/epoxy is shown in Fig. 8. Aluminum beryllium alloys are currently used for secondary structures such as equipment shelves and support structure due to low density, high stiffness, and good vibration damping characteristics. Application of these materials in primary structure requires the establishment of a database for design and manufacturing, safe manufacturing

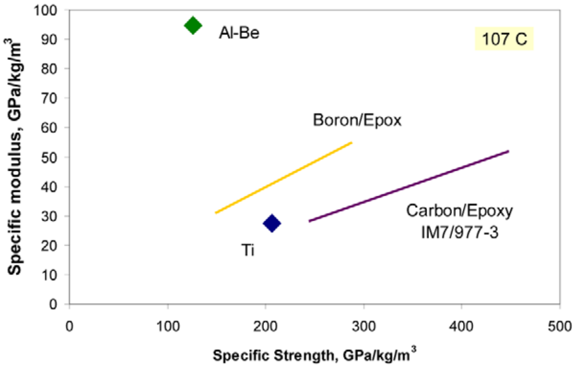

Fig. 8. Plot of density normalized stiffness vs. strength for Al-Be alloys and Boron and Carbon fiber reinforced polymer matrix composites.

practices that avoid exposure to beryllium dust and particulates, and corrosion protection methods for components in the field. Also appropriate safety protocols to control exposure to beryllium in field maintenance must be applied.

Metallic sandwich panels with periodic, open-cell cores are being developed with novel fabrication and design tools [13]. They can be fabricated using protocols based both on sheet forming of trusses and textile assembly. Analysis, testing and optimization have revealed that sandwich panels constructed with these cores sustain loads at weights greatly superior to stochastic forms and competitive with the lightest known honeycomb core systems. The benefits of the truss/textile cores over honeycombs reside in their higher specific strength at low relative density, and lower manufacturing costs.

2.1.3. Improved Al base materials for newer systems

The Airbus A380 will be the largest commercial aircraft ever built and requires the introduction of advanced and new materials—combined with new manufacturing technologies. Hinrichsen has written a series of papers that describes Airbus' selection process for new materials and processes for this advanced aircraft [14–16]. The first step in their selection process was to examine "the lessons learned" from their operations of existing Airbus fleets, including in-service experience concerning corrosion protection, inspections and repairs for

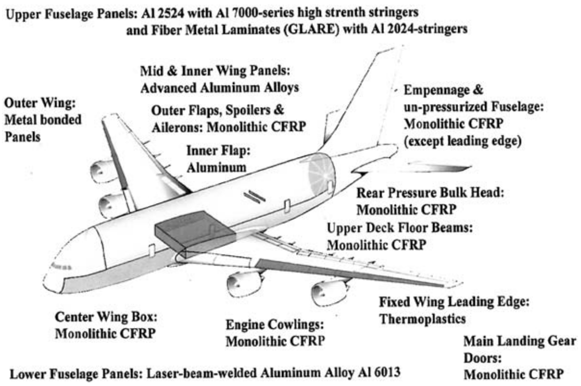

Fig. 9. Schematic depicting materials chosen for use in the new, very large Airbus A-380.

crack growth, etc. Each of their design solutions and material applications envisaged had to get approval from A380 customers with respect to inspections and repairs. Workshops with the airlines were regarded as a key element of the "technology down-selection process." The final materials selection is displayed in Fig. 9 and includes advanced aluminum alloys, carbon fiber reinforced plastics (CFRP), fiber metal laminates (GLARE) and glass thermoplastics. Note that even for this advanced aircraft, the majority of the weight of the airframe is still made of aluminum, Fig. 10. New materials, combined with new manufacturing processes, deliver the smallest portion of added value for the launch version. Hinrichsen points out that this fact is in contradiction to the perception that a new aircraft family would pioneer new technology and should take full benefit from day one. Airbus considers that a more evolutionary approach is preferred since past experience has shown that almost every new technology has some initial technical problems; water-ingress with Armid fibers and de-bonded longitudinal lap joints of metal fuselage skins were two that were mentioned by Hinrichsen. However, new materials development will continue to be monitored for possible mid-term candidates for continuous improvement with respect to weight savings, possibly replacing 2024 and 2524. Fig. 11 compares standard 2024-T3 with sheet metal material with advanced alloys and new developments with respect to fracture toughness and yield strength. Laser-beam-welding (LBW) technology has pushed the development of 6056 at Pechiney and of 6013 at ALCOA since they offer improved yield strength relative to 2024 and 2524 and can be LBW. This process replaces riveting for stringer/skin assembly in fuselage panels and adds value by reducing manufacturing costs. Aluminum-magnesium scandium alloys show materials performance similar to 2024-T3 but with much better corrosion resistance with the added benefit that they don't require complex heat treatments. The C68-type alloys are being judged as mid-term candidates due to their higher strength with respect to 2024 and 2524.

There has long been interest among the major aircraft manufacturers in producing a second-gen-

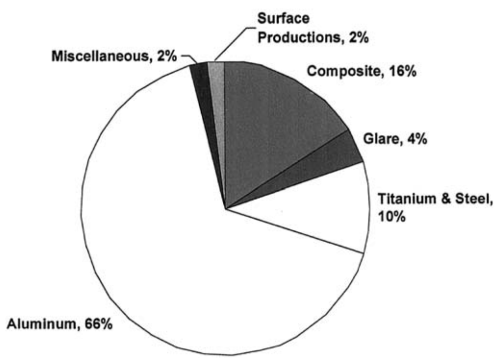

Fig. 10. Materials distribution in the A-380 by per cent of empty weight.

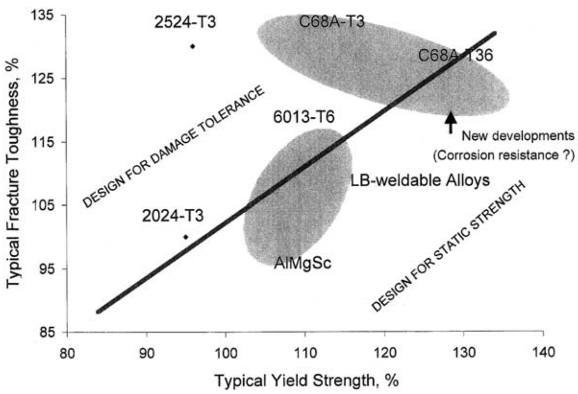

Fig. 11. Fracture toughness—yield strength domain with several alloys positioned to show their utility for deigns that are static strength or damage tolerance limited.

eration supersonic transport to operate in the long-range international market. Although there is no current active program for such an aircraft, future demands may regenerate production activity. The choice of speed for such a vehicle will be the major determinant for the materials selection for the fuselage and may range from Mach 1.6 to Mach 2.4. Aluminum alloys would be viable candidates up to Mach 2 while more expensive titanium alloys and polymer composites would be candidates for higher Mach numbers. Alloy 2618 (CM001) was selected for the primary structure of the Concorde, a Mach 2.0 airplane. The variant of 2618 that was used is a specially processed clad sheet and was selected over other candidates, such as 2024-T8, 7075-T6 and 2014, because of its static strength, fatigue strength, and especially because of its creep strength. Recent studies have shown that in order to meet the desired economy and range goals of a new SST, a weight reduction of approximately 30–33% is required compared to the projected weight of an airframe similar to that used for the Concorde but enlarged to meet the passenger requirements [17]. Following the research of Polmear [18], recent studies on a NASA program showed that small additions of Ag and Mg to 2519 could increase the peak aged tensile yield strength by 10%. The addition of small amounts of Ag and Mg stimulate the precipitation of a plate precipitate on {111}, designated Ω, in addition to the Θ’ precipitates that form on {100} of the matrix. Using computer simulations, Zhu et al [19,20] have shown that an optimum balance of {111} and {100} precipitates can increase the strength compared to alloys that contain similar volume fractions of only one type of precipitate. A number of alloys based on 2519, but with variations in Cu, Mg, and Mn and with 0.5%Ag and 0.13%Zr were examined on the NASA program. Two alloys looked particularly attractive with respect to mechanical properties and were designated C415 and C416. Tensile yield strengths and creep resistance of these alloys are significantly better than 2519-T87 and 2618-T61, Figs. 12 and 13.

2.1.4. New methods for Al alloy design

The aerospace industry, both air framers and engine manufacturers, have indicated the need for new high temperature aluminum alloys, which can operate successfully at temperatures to 150 °C for a supersonic airframe or for components of the engine. Due to economic considerations, alloy development can no longer be performed using purely empirical, trial and error approach that has been dominate over the past 100 years. Modeling and simulation, in conjunction with experiments, can be employed to improve the efficiency of alloy design, optimizing processing and manufacturing operations [21]. This approach can greatly reduce the time associated with alloy development and the generation of the knowledge base required for insertion of new materials into aerospace systems. One approach to streamline alloy design is shown schematically in Fig. 14. The first step is to select a system that offers promise for obtaining the desired

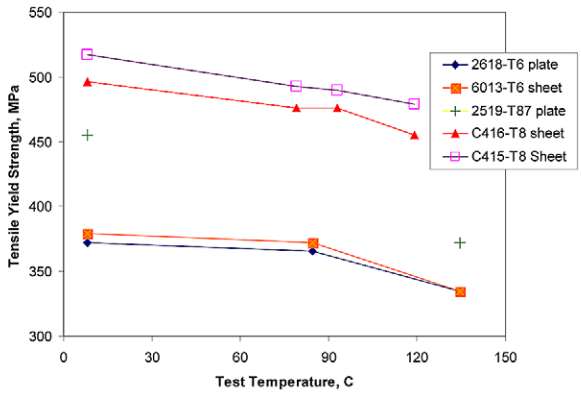

Fig. 12. Plot of temperature dependence of yield strength of several Al alloys including two new alloys.

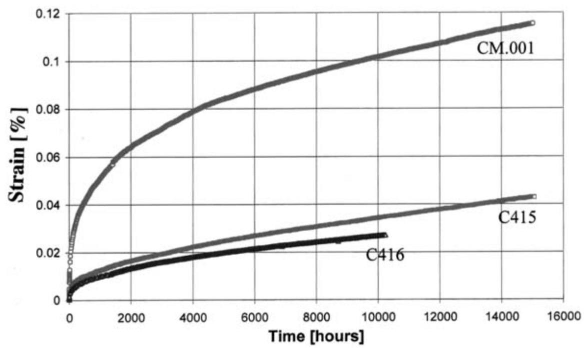

Fig. 13. Creep strain vs. time plots for three Al alloys. Tests conducted at 107°C with a load of 207 MPa.

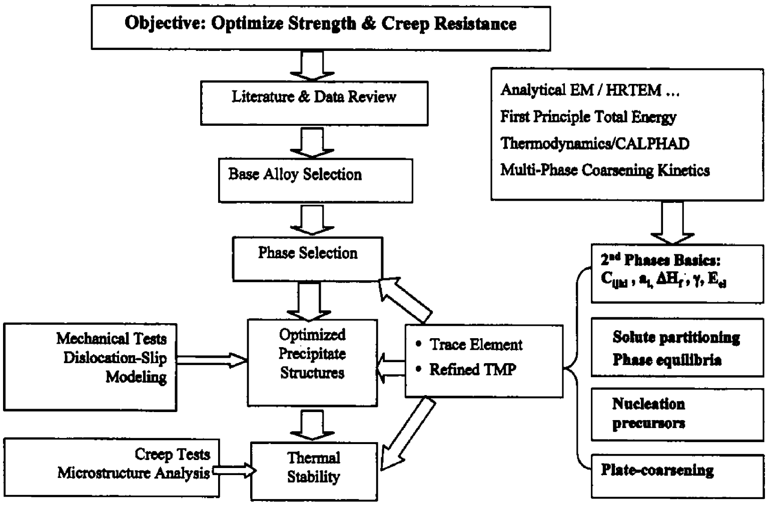

Fig. 14. Flow diagram showing main elements of a typical alloy development campaign.

microstructure and properties to meet the stated objective and this is accomplished by an extensive literature search and evaluation of available data. After selecting the system, one needs to determine the phase space that offers the greatest potential to meet the program goals.

Since phase diagrams represent the state of an alloy as a function of temperature, pressure, and alloy concentration they can be used for identifying the ideal phase field. Often times the phase diagrams for a complex alloy system have not been determined and must be calculated using programs such as CALPHAD (CALculation of PHAse Diagrams). This method is an approach to establishing equilibria among phases, through thermodynamic modeling of the individual phases based on the idea of phase competition in a system. The phases are modeled according to the phase stabilities, measured thermodynamic properties, and the measured transus points (including liquidus, solidus, eutectic, etc). An article by Kattner [22] presents an excellent overview of the use of thermodynamic functions for the calculation of phase diagrams. Such a calculation reduces the effort required to determine equilibrium conditions in a multi-component system. Dubost [23] has illustrated the industrial application and determination of equilibrium phase diagrams for light alloys, e.g. aluminum. Materials design can now be viewed as the best application of available models for the prediction of synthesis of alloys with desired properties. Of course, all theoretical calculations must be verified experimentally, but the experiments should be based on sound theory and not on a trial and error approach.

Once the alloy system and phase field have been identified, the desired optimum precipitate structure and morphology for maximum strength may be determined from a dislocation simulation method [19]. The knowledge gained through the simulation method has been verified in some aluminum alloys [19]. For alloys for high temperature application, the thermal stability of the precipitate structure is important and one must consider both phase coarsening and phase competition. Coarsening of a single second phase is thermodynamically attributed to the tendency for decreasing the total interfacial energy between the second phase and the aluminum matrix. The interfacial energy consists of the chemical energy and the associated strain energy. First principle calculations using programs, such as the Vienna ab initio simulation program (VASP) [24] may be used to calculate interfacial energies and changes in total and interfacial energy by the addition of selected trace elements to either the interface or the internal precipitate structure. Such calculations will aid in the selection of trace elements that, hopefully, will reduce the coarsening of the precipitates without using a trial and error method. This program may also be used to verify crystal structures and to calculate elastic constants. Quantitative data of the elastic constants for the second phases are significant and fundamental for determining the strengthening mechanisms. These parameters also play a role in determining the habit plane and the evolution of equilibrium shapes of the second phase particles since they determine the elastic strain energy associated with lattice misfit. Once candidate alloys (and microstructures) have been identified the methodology must be evaluated with mechanical property tests, etc. but such an approach should lead to streamlined alloy design and therefore aid in the early insertion of new high performance materials.

2.1.5. Ti alloy usage in aircraft

Ti alloys have been used for special purpose applications in both military and commercial aircraft for several decades. In addition to the high speed military airplane, the SR-71, described earlier, there are a number of applications of Ti alloys for heavily loaded structure such as bulkheads in fighter aircraft, the wingbox on the B1-B bomber and the landing gear beam in the Boeing 747. These components are illustrated in Figs. 15–17. In each of these cases, Ti alloys were chosen because, compared to Al alloys, they have equal or better density corrected strength, good damage tolerance and excellent corrosion resistance. The alloys chosen for each of these three applications is the old, but still widely used $\alpha + \beta$ alloy, Ti-6Al-4V (Ti-6-4). Higher strength $\alpha + \beta$ and β Ti alloys are available, but the damage tolerance, both toughness and crack growth, typically decreases in the higher strength alloys. For fracture critical structures, i.e. those that are sized for static strength, the critical flaw size prior to the onset of unstable crack extension is proportional to the parameter $(K_{Ic}/YS)^2$. Thus incorporation of higher strength alloys without a commensurate increase in toughness increases the risk of catastrophic failure which is generally unacceptable. In addition to the intrin-

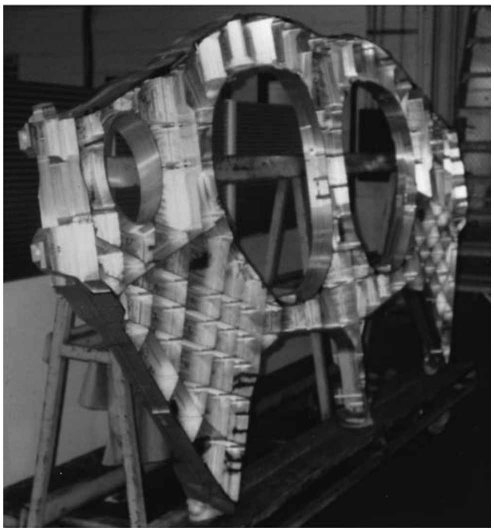

Fig. 15. Photos of a forged and machined Ti alloy bulkhead for a fighter aircraft.

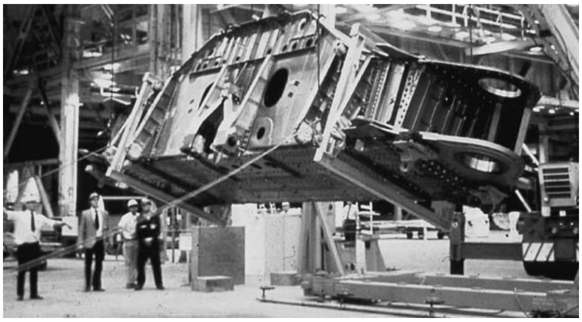

Fig. 16. Photo of the wing box of the B1-B bomber aircraft made by diffusion bonding.

Fig. 17. Photo of the Ti alloys forged and machined landing gear beam for the Boeing 747.

sic mechanical properties of Ti alloys, the corrosion resistance makes them attractive, especially for components that are embedded in the aircraft and, as a consequence, are very difficult to inspect for corrosion attack. The better resistance to general corrosion and essential immunity to exfoliation corrosion compared to high strength Al alloys is an advantage for Ti alloys. Ti alloys are also used in circumstances where their higher strength allows the same load to be carried by a physically smaller structural member, even though there is no weight advantage because of the higher density of Ti alloys. An example of the latter situation is the landing gear beam shown in Fig. 17. From a strict structural efficiency standpoint, Al alloys would be comparable and considerably less expensive. However, had an Al alloy been selected, the landing gear beam would not have fit within the available space in the airframe fuselage, thereby creating an aerodynamic penalty.

Ti alloys are also a very good alternative to high strength steel, even though at the highest strength levels, the structural efficiency achievable with steel is considerably higher. The issue here is that the susceptibility of steel to hydrogen embrittlement becomes much higher at strength levels $>$1250 MPa. Using steel at strengths higher than this requires use of a protective coating such as paint or plating with Cd or Cr. The former of these approaches requires periodic maintenance to repair scratches and chips and the latter of these is being phased out for environmental and health hazard reasons. The landing gear of most commercial aircraft has traditionally been made of high strength steel such as AISI 4340 heat treated to strengths of 1800–1900 MPa. Service history has shown that numerous hydrogen embrittlement failures have been experienced, despite the use of stringent maintenance procedures. Recently, a high strength β alloy, Ti-10V-2Fe-3Al (Ti-10-2-3), has been selected for the landing gear of the Boeing 777. For this application, Ti-10-2-3 is heat treated to the 1250 MPa strength level. The decision to use Ti-10-2-3 is driven by the ability to achieve weight reduction and eliminate the risk of hydrogen embrittlement failure, albeit at an increase in cost. This is a good example of added customer value directly attributable to materials. The B-777 landing gear is shown in Fig. 18. The new, very large Airbus aircraft (A-380) mentioned earlier appears to be committed to a Ti alloy landing gear also, although the choice of alloy has not been finalized. The driver for this selection is also weight reduction and, perhaps, available space if Al alloys are being considered. This relatively new application of Ti alloys for landing gear is made possible by the advancement in β alloy understanding and production capability.

Another relatively new application of β alloys in large aircraft is for springs. These Ti alloy springs replace steel springs at a significant weight reduction and also eliminate the need for protection by painting. Because springs are generally loaded in torsion, fracture is a lesser concern. Consequently β alloys with very high strengths but low tensile ductility can be used safely. The alloys are cold drawn or rolled, coiled into springs and aged to achieve strengths in excess of 1400 MPa. The relatively low modulus of β alloys (60–100 GPa) coupled with the high yield strength permits a very large elastic displacement range for the spring,

Fig. 18. Photo the landing gear assembly for the Boeing 777. The horizontal forging is Ti-10-2-3 and is the largest β alloy forging in use today.

which also can be beneficial. Examples of several β alloy springs are shown in Fig. 19. Several β Ti alloys are commonly used for springs including Ti-3Al-8V-6Cr-4Mo-4Zr (Beta C) and Ti-15V-3Cr-3Al-3Sn.

Ti alloys are also being used in aircraft under circumstances where the corrosion resistance is the prime consideration. Ti alloys exhibit good galvanic compatibility when placed in contact with carbon fiber composites, whereas Al alloys do not. Consequently, as the use of composites increases with each generation of aircraft, the need to use Ti alloys for fittings and attachments for mitigation of galvanic corrosion also has increased. These fittings and attachments often are not heavily loaded and, therefore represent prime opportunities to use Ti castings which are less costly than machined forgings or fabricated components. Ti casting technology has progressed in the past 15–20 years to the point that complex net shapes are producible. Such castings have been in use in aircraft engines for a number of years but the aircraft designers have been slow to adopt this technology. An example of a casting that is used on a military cargo aircraft is shown in Fig. 20. This single piece casting replaces a fabricated part made up of 22 pieces resulting in major cost savings. Ti alloy castings that have been hot isostatically pressed (HIP'd) exhibit no porosity and therefore have fatigue strength that is comparable to wrought products with the same microstructure. This is in contrast to the situation for Al alloys where gas induced porosity is common and such porosity cannot be closed by HIP processing. This has led to the use of a casting factor for Al castings, which serves to penalize their structural efficiency. There is no comparable need in the case of HIP'd Ti alloy castings, making the design process more straight forward and yielding more attractive results in terms of structural efficiency. This point also will be mentioned again in connection with Ti usage in aircraft engines.

Fig. 19. Photo showing three types of β alloy springs used in Boeing aircraft.

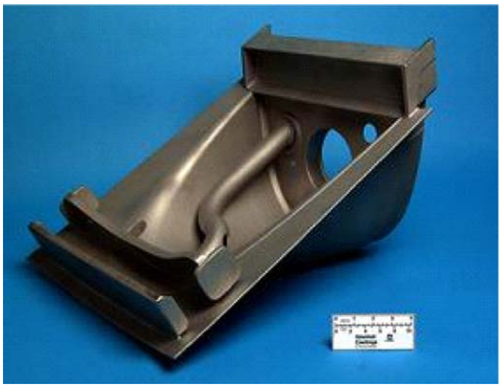

Fig. 20. Photo of a Ti alloy casting for use in a large military transport aircraft.

Another alternative to machining forgings or machining plate to create a rib-on-plate geometry is a new process known as laser additive manufacturing. In this process, powder is fed into a laser beam which fuses it and deposits the molten metal on a flat substrate, creating an upstanding rib. This rib is not necessarily straight and can take on a curved shape because the work piece moves under the laser and is guided by a computerized numerically controlled servo mechanism in the same way as a machine tool would be in a CNC machine. This process, while still under development, exhibits its promise for making net shapes where alternative processes would require removal of as much as 80% of the starting weight in some cases. There are unanswered questions about this process including the cost of powder and the ability to control porosity, but it is an attractive means of increasing the utilization of input material, especially for designs where there are deep pockets that would have to be created by machining. An

Fig. 21. Ti alloy shape with a deep pocket made by laser additive manufacturing.

example of a part made by laser additive manufacturing is shown in Fig. 21.

Finally, the use of high strength Ti alloys for helicopter rotors has enabled the operation of the aircraft at higher gross weights than was originally intended. In one example, the rotor material of a Westland helicopter was changed from Ti-6-4 to the higher strength Ti-10-2-3 β alloy which permitted the aircraft gross weight to be increased from ~3860 to 5585 kg. This provided major customer value by avoiding development of an entirely new system. These rotors consist of three individual forgings as is illustrated in Fig. 22. The fatigue sensitivity of helicopter rotors is extreme, thus the availability of high strength β alloys was the key element in this system modification.

In summary, Ti alloy usage in aircraft, expressed as a percentage of empty weight, is increasing relative to Al alloys and steel with each new product generation. For example, the original Boeing 747-100 contained about 2.6% Ti whereas the Boeing 777 contains about 8.3%. This usually adds to the initial aircraft cost which creates the need to demonstrate a commensurate contribution to customer value. The decision to use Ti alloys, therefore, must be determined by the trade-off between cost and customer value. Weight reduction, lower maintenance cost and improved reliability all are aspects of customer value that may be used to justify the use of Ti alloys.

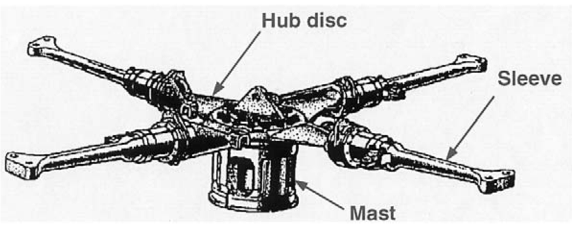

Fig. 22. Drawing of a helicopter rotor assembly showing three parts that were changed from Ti-6-4 to Ti-10-2-3 to enable a gross weight increase.

2.2. Evolution of propulsion systems and the role of materials

In a similar fashion to the evolution of the design methods for airframes, design methods for aircraft engines also have evolved and improved. The improvements are based both on lessons learned from field experience and on the availability of better computer based design tools. Materials with improved capability also are required to enable realization of the full potential of these designs. In the case of engine materials, there are several discrete materials requirements that drive changes in materials or processing methods: higher strength, better damage tolerance, absence of material defects and, in some cases, higher temperature capability. In terms of percent by weight, the principal materials of construction for gas turbine engines are Ti alloys and Ni base superalloys. High strength steel is used for the main shaft and for bearings and there also are a few applications of polymer matrix-carbon fiber composites. Due to length limitations, the focus of this paper will be Ti and Ni alloys.

A modern subsonic aircraft engine for a passenger or transport aircraft consists of discrete sections or modules: fan, low pressure compressor (LPC), high pressure compressor (HPC), combustor, high pressure turbine (HPT) and low pressure turbine (LPT). Generally, the fan, LPC and about 2/3 of the HPC are made from Ti alloys, whereas the balance of the HPC, all of the combustor and both the HPT and the LPT are made from Ni base alloys. This transition from Ti to Ni alloys is dictated by the respective operating temperature capability of these materials. An example of such an engine is shown in Fig. 23. These engines can be very large; the fan diameter of the engine on the Boeing 777-300LR is >3 m and the engine weighs >7300 kg.

While weight is important for aircraft engines, the options available to reduce weight are fewer compared to aircraft because of the high loads placed on the major components during service and because of the high operating temperatures. The most common weight-related figure of merit for engines is the ratio of thrust to weight, also called specific thrust. Therefore, higher specific thrust achieved, for example, by increasing maximum operating stresses or temperatures often is considered as important as weight reduction per se. Particularly in commercial engines, reliability and durability have become key product characteristics. The trend in large commercial aircraft favors twin engine designs, such as the Boeing 767, the Airbus 310, the Airbus 330 and the Boeing 777. This creates a requirement for a high degree of engine reliability because these aircraft all operate on long over-water routes. The US Federal Aviation Agency and the European Joint Aviation Authority have explicit criteria for certifying an airplane/engine combination for such routes. The rating is called Extended Twin-engine Operations (ETOPS). The ETOPS rating is expressed in minutes and higher ETOPS ratings enable a longer the over-water portion of the total flight. Higher ETOPS ratings make more direct routes to be flown. This impacts total fuel consumptions and flying time, both of which are important to the airlines. In-flight shutdowns of engines negatively impact the ETOPS rating. Therefore, materials related in-flight shutdowns are unacceptable. This creates the requirement for a high degree of confidence before a new material is introduced into an engine.

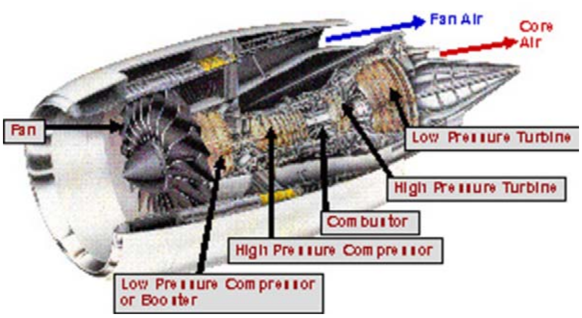

Fig. 23. Large commercial turbofan engine showing the six modules.

Durability, especially in the turbine section, dictates the number of hours an engine remains in service before it must be removed for maintenance. Over the past 30 years, the durability of aircraft engines has improved dramatically, especially in the case of commercial products. Improved durability means better utilization of the aircraft and typically lower operating costs, both of which are important to the operator. When the Boeing 707 first entered service in the 1950's the engines typically were removed for maintenance after about 500 hours of operation. Much of the need for removal was related to performance deterioration of the HPT. Today, a Boeing 747 class engine remains on wing for more than 20,000 hours. This remarkable improvement is in part due to more robust designs and in part due to better materials. When it also is considered that engine operating temperatures have increased significantly to improve fuel economy, the impact of better materials becomes even clearer. Finally, it is essential that engine materials, especially those used in the rotating parts of the engine be free of any defects from melting or forging. From a practical standpoint, it is physically impossible to design an engine that can contain a burst rotor. Therefore the integrity of the rotors becomes a matter of serious concern with regard to flight safety. Better damage tolerance coupled with intense efforts to eliminate both intrinsic material defects and manufacturing induced defects has led to major improvements in rotor integrity over the past 20 years. The efforts to eliminate materials defects represent contributions from many specialties ranging from melting and forging to non-destructive evaluation. Improvements in damage tolerance has come from an improved understanding of microstructure-property relationships in Ti and Ni alloys much in the same way as has been described previously for Al alloys.

2.2.1. Evolutionary improvement in Ti alloys for aircraft engines

Because of excellent specific strength, good damage tolerant properties, temperature capability up to 600 °C and well-established manufacturing process capability, Ti alloys make excellent materials for the cooler portions of aircraft engines. Especially in the fan, where the stresses on the disk are very high, it is essential to use premium quality Ti alloys to minimize the incidence of material defects. There are several types of materials; those that are melt related and those that are caused during forging. Among these, the most serious are the melt related defects, especially the interstitial stabilized inclusions, called hard α or Type I defects. These defects are essentially hard, brittle inclusions containing as much as ~10wt% nitrogen, typically in the form of TiN. Because of the brittle nature of the inclusions and the high operating stresses in the rotors, hard α is essentially an incipient crack which begin to propagate starting with the first cycle on the engine. A great deal of effort has been exerted to minimize the occurrence of these defects and the rate of occurrence now is on the order of 1 per million kg of rotor grade material produced. This represents a 5–10× reduction over 35 years ago.

Ti alloys also are costly and therefore it is common to re-use turnings and chips generated when forgings are machined to create the final Ti alloy components. This practice, which is common in the industry and which is an economic necessity, creates the possibility of accidentally incorporating WC inclusions from broken machine tools into the final material. These WC, melt-related defects are called high density inclusions (HDI). Strict management of the turnings and chips, including 100% radiographic inspection, has reduced the incidence of HDIs to relatively low levels also.

Driven by concern over the consequences of materials defects, production methods for premium quality or rotor grade Ti alloys has evolved over the past 40 years through a number of incremental changes. These changes include sponge quality, handling of scrap, VAR electrode preparation, hot top practice during melting and melt rate control. The attendant increase in material reliability has permitted designers to use higher operating stresses than were initially the case. In the past 5 years a major shift in Ti alloy melting practice has occurred. Historically rotor grade Ti alloys were melted by vacuum arc re-melting (VAR) and then re-melted two additional times to produce sound, homogeneous ingots. The product of this process is called triple melt VAR materials. Today, a process known as hearth melting is being used to produce much of the rotor grade material for jet engines. Hearth melting is done in a furnace that uses a water-cooled copper hearth and either plasma torches or electron beam guns as the source of heat for melting. The heat extraction from the hearth is carefully managed to ensure that a thin layer of solid Ti alloy (called a skull) remains and is in direct contact with the hearth. The skull separates the molten Ti alloy and the copper hearth. Thus the Ti alloy being hearth melted only contacts Ti alloy during the time it is in a molten state. The material to be melted is fed into one end of the hearth, is melted by the heat sources, and flows into a water cooled mold at the other end of the hearth. When turnings are used, any WC particle sink and are trapped in the skull and cannot be included in the final ingot. Hearth melting and VAR melting including schematic illustrations are described in more detail elsewhere [25].

Other types of material defects also are observed in forged Ti alloy products, either billet or final forgings include β flecks, strain induced porosity and blocky α. Each of these has the potential to reduce the fatigue life of the material and none are allowed in rotor grade material. Among these, β flecks are caused by solute segregation during solidification of the ingot, strain induced porosity is caused by improper mill practice when the ingot is converted to billet and blocky α is the result of improper reheat practice during the final forging operation. The defects just described can occur in essentially any of the commonly used $\alpha + \beta$ Ti alloys, although the propensity for β flecks is more pronounced in those alloys containing β eutectoid alloying elements such as Cr, Fe or Cu. The use of modeling of ingot solidification and billet conversion processes has been helpful in identifying process parameters that eliminate these defects. If the process windows that have been defined by modeling are broad to be practical and are carefully followed, these defects can be eliminated. This represents an important accomplishment in improving materials reliability for jet engines and other comparably demanding applications.

Jet engine rotors are manufactured from forgings or rolled rings. The fan disk is typically a large, single-piece forging. An example of a fan disk after final machining is shown in Fig. 24. From a weight standpoint, it is beneficial to use a higher strength alloy for the fan disk and the two most common alloys (in addition to Ti-6-4) are Ti-5Al-2Zr-2Sn-4Cr-4Mo (Ti-17) or Ti-6Al-2Sn-4Zr-6Mo (Ti-6-2-4-6). The limiting properties for the fan disk (at a given strength) are low cycle fatigue (LCF) and fatigue crack growth. Attention to processing can optimize these particular properties and β forging is now commonly used to create a Widmanstatten microstructure. This structure reduces crack growth without an unacceptable penalty in LCF life. Ten years ago it was not possible to do this because the control of the forging process was not adequate to provide reproducible structures. In contrast, the compressor rotor, also called a spool, is a multi-stage component frequently made from several forgings or rolled rings and joined together before machining. The compressor spool can incorporate as many as 7 compressor stages into a single component, as shown in Fig. 25. The compressor spool is typically Ti-6-4 in the first 5 stages with the last 2 stages being a higher creep strength alloy such as Ti-6Al-2Sn-4Zr-2Mo+Si (Ti-6-2-4-2S). The front stages of the spool are LCF limited and the final 2 stages are creep limited. Here, the Ti-6-4 stages are $\alpha + \beta$ forged and the Ti-6-2-4-2S stages are β forged and the pieces are joined by inertia (friction) welding. The benefit of the spool construction is the absence of bolted joints between stages with a resulting lower risk of fatigue crack initiation at bolt holes. The final stages of the HP compressor rotor are made from Ni base alloys because the operating temperatures exceed the capability of Ti alloys. The use of Ni base alloys in jet engines will be discussed in a later section.

In addition to the highly stressed rotors, the fan blades and at least 6–8 stages (depending on the particular engine) of the compressor air foils also typically are made from Ti alloys. These components are typically life limited by high cycle fatigue (HCF), although resistance to impact damage from foreign objects also is important. The HCF strength of Ti alloys usually scales with the yield stress, so the use of higher strength alloys than Ti-6-4 is attractive in principle. In practice, the difficulty of

Fig. 24. Photo of a forged and machined Ti alloy fan disk for a large commercial aero-engine.

Fig. 25. Photo of a Ti alloy seven stage HPC spool after forging, inertia welding and final machining.

manufacturing net shape air foils from higher strength alloys is significantly greater and the decision to use a higher strength alloy represents an economic trade-off that is ultimately made on the basis of customer value. Thus most of the fan and compressor air foils in service in commercial engines today are made from Ti-6-4. There are some exceptions driven by severe fatigue sensitivity or by the occurrence of aero elastic excitations. In the former case, the higher strength alloy Ti-4Al-4Mo-2Sn (known as IMI-550) is used and in the latter case, the higher modulus alloy Ti-8Al-1Mo-1V (Ti-8-1-1) is used. Increasing Al content raises Young's modulus of α+β Ti alloys and this changes the natural resonant frequency of the air foil. The latest generation of very large engines for the Boeing 777 (cf Fig. 23) has such large fans that weight becomes an issue. Consequently, these fan blades are either a hollow Ti alloy part made by super plastic forming and diffusion bonding or are made from solid polymer matrix carbon fiber composites. Both of these solutions are expensive responses to design requirements, but are the only available means of creating very large diameter turbofan engines.

Ti alloys are also used for static components in jet engines. Included are frames, casings, manifolds, ducts and tubes. The largest use today is cast frames because they can be produced in near net shape and can replace a fabricated component comprised of dozens of individual parts. Even though the castings are relatively expensive, they represent a significant cost reduction compared to the fabricated part. A typical cast Ti alloy front frame is shown in Fig. 26. As was discussed in the airframe case, these castings are HIPd to eliminate any porosity. In many instances, the engine mount is an integral part of these frames so having reproducible property values is important to assure integrity of the design.

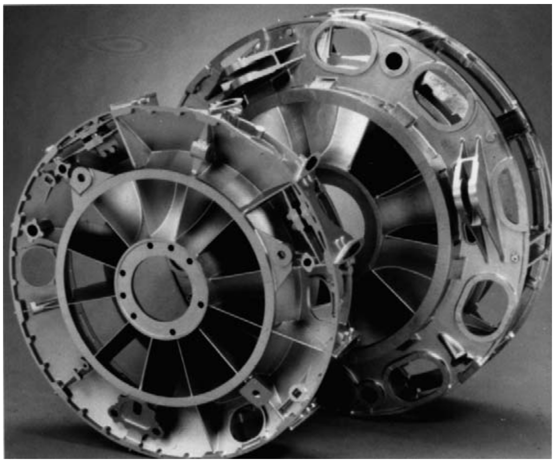

Fig. 26. Photos of two cast Ti alloy engine frames showing the detail that can be achieved by the casting process.

2.2.2. *Improved Ti alloys for new propulsion systems*

By comparison to Al alloys, there has been less effort devoted to developing and commercializing new Ti alloys and very little success in introducing new alloys into aircraft engines. There are several reasons for this. First, the volume of Ti alloys used is small compared to that of Al alloys, so amortizing development cost is more difficult. Second, the qualification cost for a new rotor alloy is very high because of the inherent risk of rotor failure. This cost–risk combination becomes an unavoidable deterrent to introduction of a new alloy. Third, the application requirements typically preclude realization of any benefit from improvement of a single property. A possible exception to this situation would be the availability of an alloy with significantly higher temperature capability. Such an alloy could displace one or more Ni alloy stages from the rear of the compressor with a significant weight benefit. A relatively new alloy Ti-5.8Al-4Sn-3.5Zr-0.5Mo-0.7Nb-0.35Si-0.06C (IMI 834) with a 50 °C increased temperature capability has been developed in the UK. This alloy is attractive technically but there is only one IMI834 producer world-wide which makes it commercially unattractive. Consequently, it has not been widely adopted despite its attractive properties.

In addition to conventional $\alpha + \beta$ Ti alloys, a lot of effort has been devoted to developing Ti-based intermetallic compounds for high temperature applications. These compounds are based on the phases Ti_3Al, Ti_2AlNb and TiAl. While each of these has the potential for higher temperature use, there are issues associated with low ductility, environmental sensitivity and cost that have prevented their application until now. This situation is analogous to the revolutionary Al alloy technology described earlier. There is reason to believe that limited applications of TiAl based materials will occur when the need for higher temperature, low density alloys is great enough. Market pull and customer value will be the determinant here, not materials technology.

2.2.3. Evolutionary improvement in Ni alloys for aircraft engines

At temperatures above ~550 °C, Ni base alloys are used instead of Ti alloys. This means the rear of the compressor, the combustor and the entire turbine sections are made of Ni base alloys. Early in the development of the jet engine, the temperature capability of the early generation Ni base alloys was the main limitation in achieving higher performance through increased operating temperatures. The current alloys have minimized this limitation although newer designs could benefit from higher temperature capability than is available today, especially at the rear of the HPC. It is common in rotor design to restrict the operating stresses to levels that eliminate creep as a life limiting consideration. Consequently, LCF life and fatigue crack growth become the limiting properties just as in the case of Ti alloy rotors. Over the past 25 years, Ni base rotor alloys have evolved in terms of temperature capability. This is shown in Fig. 27. This figure compares the creep strength of two classes of Ni base alloys; those produced by ingot metallurgy (IM) and those that are produced by powder metallurgy (PM).

The IM alloys generally contain lower total concentrations of alloying additions and have lower creep strength than PM alloys. They also are significantly less expensive to make and fabricate. As was the case for Ti alloys, melting technology for ingot metallurgy Ni base alloys also has evolved over the past ~35 years. Today triple melting is commonly practiced to ensure composition and inclusion control and homogeneity of the final product. In the case of Ni base alloys, triple melt practice starts with a vacuum induction first melt, followed by an electroslag second remelt and a final VAR melt. This practice has led to a major reduction of melt related defects such as freckles and white spots and large inclusions that were the cause of rotor failures during the early days of Ni base alloy rotor development. As a consequence of these improvements, with the exception of the inherent temperature limitations of IM alloys, these materials are excellent in terms of reproducibility and reliability.

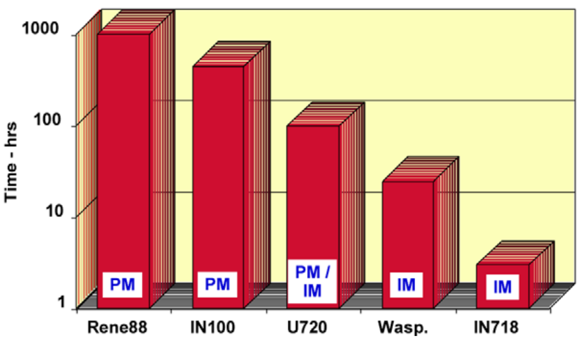

Fig. 27. Comparison of the creep strength of five Ni base disk alloys. Time is for 0.2% strain at 650 °C at a stress of 800 MPa.

The use of powder metallurgy (PM) technology to make turbine disks also has evolved since its inception ~25 years ago. Alloys are made into powder if they contain such high concentrations of solute that large (>30 cm diameter) ingots cannot be cast without having unacceptable levels of freezing segregation. The use of PM methods for producing rotor alloys solves this problem but requires the utmost care. For example, a highly disciplined powder handling process is essential to avoid accidental incorporation of unwanted contaminants that can have deleterious effects on fatigue behavior. A single, large inclusion in a high stress region of a rotor can cause a rotor burst with disastrous consequences.

A typical processing sequence is as follows:

1. Inert gas atomization to form powder;
2. Screening of the powder to a predetermined maximum powder particle size, typically −270 mesh (44 μm);
3. Vacuum degassing of the powder
4. Placing the powder in an extrusion can
5. Extruding the powder into a billet using an extrusion ratio that assures full density;
6. Forging the billet into a final forged part, often by an isothermal, hot die forging process.

One reason to include this process outline is to emphasize the cost of using PM disks.

Ni base alloys contain reactive elements such as Al and refractory element additions for solid solution and precipitation strengthening. These reactive elements can form small oxide particles during inert gas atomization, even under the most tightly controlled circumstances. These small oxide particles can serve as premature fatigue crack initiation sites. Because they are not uniform in size and are not uniformly distributed throughout the volume of the disk, a different methodology is required to calculate the cyclic life as a function of stress distribution. This requirement has led to development of an elaborate probabilistic approach to accounting for the effect of inclusions on fatigue life. Use of this method is necessary but also creates an added cost, even after the initial data base has been generated. The remaining aspect of Ni base rotor alloy performance is the effect of grain size on critical properties including tensile strength, creep strength, LCF life and fatigue crack growth rate. The impact of grain size on each of these properties is shown in Fig. 28, which is a schematic derived from actual data. From this diagram it can be seen that LCF life and strength have opposite grain size dependence to creep strength and fatigue crack growth. Thus a processing method must be chosen that suits the particular life limiting property for the design under consideration. This ability to tailor properties is a potential benefit and the current level of understanding of property trade-offs is the cumulative result of numerous studies by many investigators.

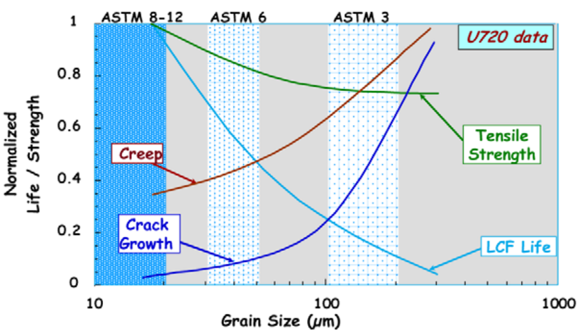

Fig. 28. Schematic drawing based on real data showing effect of grain size on creep, low cycle fatigue life, fatigue crack growth rate and tensile strength.

Finally, the HP turbine air foils are perhaps the most critical component in a modern gas turbine engine, in terms of both time between overhaul and performance. Creep strength and oxidation resistance usually are the life limiting properties of turbine air foils. Turbine air foil production technology also has evolved. The early airfoils were forged but the creep strength of the forged material was a severe limitation. Today, these air foils are cast Ni base alloys made by a highly sophisticated controlled solidification process. The processing evolution for turbine air foils can be traced from equiaxed fine grained forgings to coarse grained equiaxed castings to a columnar grain structure produced by directional solidification and finally to a monocrystal structure which is essential free of high angle grain boundaries. The creep mechanism of grain boundary sliding limits the temperature capability of the forged and equiaxed cast products. This mechanism is minimized in the columnar grain structure but still occurs. Grain boundary cracking is an issue in Ni base alloys but can be mitigated with alloying additions such as B, Zr and Hf. These elements are necessary but are not helpful to the creep strength. In the monocrystal structure, there are no large angle grain boundaries to undergo sliding or to crack so the rate controlling mechanism shifts back to intragranular flow by climb and glide of dislocations. Monocrystal alloys also require minimal or no grain boundary strengthening additions, which also is beneficial to creep strength. The macrostructures of the three types of cast air foils are Fig. 29.

Alloy composition also has a major influence on both creep and oxidation behavior. The combined effects of alloy composition and casting method on temperature capability are shown in Fig. 30. In this figure, each generation of alloy, e.g., N4 to N5 contains a higher concentration of slow diffusing refractory alloying elements which reduces the creep rate, especially in monocrystals. An interesting comparison in the figure is N4 vs. DS R142, which shows that composition effects can be as powerful as grain structure effects. Directionally solidification process is more economical than that used to create monocrystals, therefore DS airfoils

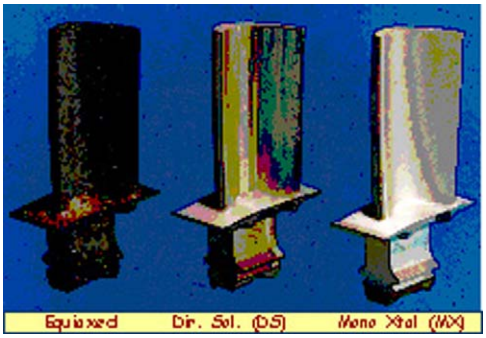

Fig. 29. Photos of three cast Ni base turbine blades macro-etched to showing the effect of the solidification process on the grain structure. (Courtesy Howmet Corporation).

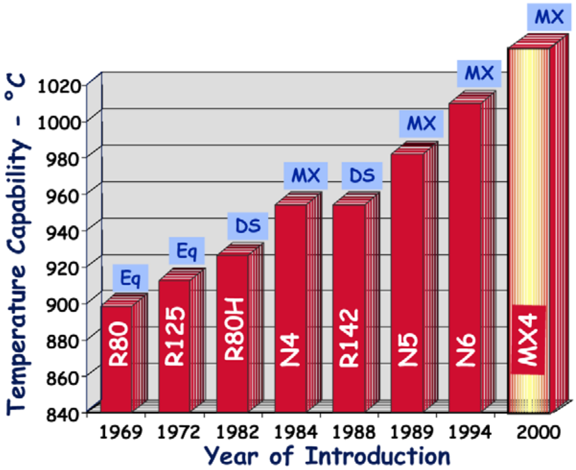

Fig. 30. Comparison of the creep strength of eight Ni base turbine blade alloys. Temperature is for constant rupture time at the same stress.

are still used in less demanding application such as the second stage of the HP turbine and in the LP turbine.

These cast air foils are often air cooled using bleed air from the compressor. It is now becoming commonplace to apply a 125 μm thick ceramic coating on the surface of the air foil. This coating is called a thermal barrier coating (TBC) and reduces the heat flux through the air foil wall which permits greater gas-metal temperature differences to be maintained during engine operation. Modern, high performance gas turbines typically operate at maximum gas temperatures at the turbine entrance of 1450–1500 °C. This is considerably higher than the metal capability but is possible because of the use of air cooling (Fig. 31).

3. Closure

The availability of improved materials has enabled the continuous improvement in capability of aircraft and aircraft propulsion. In combination, enhanced materials capability, improved materials processing methods and more efficient design methods account for the existence of modern aircraft that can fly more than 20,000Km non-stop. Concurrently, the noise and emissions from current generation commercial aircraft are considerably lower than ever before. As the capability of modern aircraft has been enhanced, the simultaneous improvement in reliability of propulsion systems has evolved. The current high levels of reliability in current propulsion systems has enabled twin engine aircraft to fly long over water routes that were previously reserved for three and four engine aircraft. This has added considerable customer value.

Improvements in materials will continue to be made possible by new computation methods, advances in modeling and simulation both for alloy and process design, new sensing devices for process control, and the ability to tailor materials to specific applications. There will also be changes in structural concepts directed towards lowering the costs of manufacture and saving weight. These include integral stiffening/iso and ortho grid con-

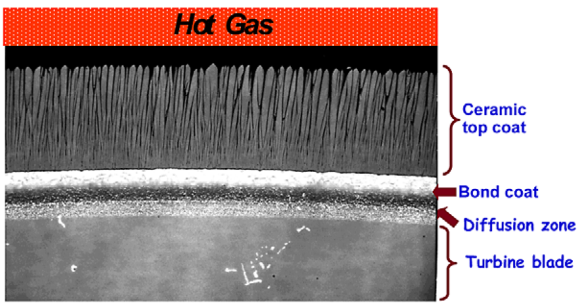

Fig. 31. Cross section of a turbine blade with the TBC on it showing the columnar structure of the TBC, the bond coat and the diffusion zone in the bond coat base metal interface.

struction, precision structural castings, superplastically formed parts, and welded structures. New manufacturing methods may require modification in existing materials or the development of new materials that would be conducive to these new technologies. Economic considerations have resulted in current aircraft operating well beyond their original design life bringing to the forefront issues of materials stability, corrosion resistance, fatigue behavior, and maintenance procedures. Evaluation of new materials, either for retrofitting older aircraft or for new systems, must include the costs associated with their qualification, as well as an assessment of performance and operating costs over the entire life cycle of the aircraft, from fabrication to maintenance.

While the focus of this paper is on aircraft and aircraft engines, many of the messages also pertain to automobiles in a general way. The need for improved fuel economy, driven by government and by competitive pressures, has created a heightened interest in lightweight automotive structures. Clearly, any experience from the aircraft industry will need to be viewed in light of the differences in requirements of the automotive industry. Central to these differences are expected product lifetime and cost. The added cost to reduce the weight of an airplane is amortized over more than a 30 year life whereas for an auto it is more like 5–10 years. The possible exception to these significant differences, and the product which has the closest parallel to aircraft requirements, is over large highway trucks. In the case of trucks, the differences compared to aircraft are smaller because of the longer product life, higher duty cycle and the fixed maximum weight, at least in the US, which provides a direct economic incentive to pay more for lighter vehicles. A similar situation could evolve for autos if the government mandated fuel economy standards become more stringent. Fuel prices are increasing but, unto itself, this has proven to be insufficient motivation to pay much more for a lighter auto. Speculation about the influence of regulatory pressures on product trends has been historically ineffective, largely because the regulatory trends have not been introduced on the right timescale and because they have not always exhibited constancy of purpose.

Nevertheless, the wealth of experience available from the aircraft industry can be valuable as demands for lighter structures in a variety of products becomes more important.

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