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Recent Titanium Developments and Applications in the Aerospace Industry

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New alloys, advances in processing development and new applications since the last International Titanium Conference in 2003 will be discussed with regard to airframe structures. There have been significant developments in the aircraft industry driven by new aircraft such as the Airbus A-380 and Boeing 787 commercial aircraft and the Boeing C-17 and Lockheed Martin F-22 and F-35 military aircraft; these and others will be discussed. With regard to alloy development, subjects for discussion include Ti-5Al-5Mo-5V-3Cr, more machinable alloys, and metal matrix composites with continuous and discontinuous reinforcement. In terms of processing, items such as welding, direct metal deposition or metal additive manufacturing, machining, superplastic forming, and Ti-5Al-5Mo-5V-3Cr forgings will be covered. Post-fabrication issues are also key to the successful utilization of titanium and progress in these areas will also be described.

Keywords: *Ti-5A1-5Mo-5V-3Cr, aerospace applications, welding, single melt plate, machining, superplastic forming ,titanium matrix composite , direct metal deposition, die forgings, modeling*

1. Introduction

The status of the titanium industry has changed dramatically since the last international conference in Hamburg, Germany, in 2003. With the development of the Boeing 787 and numerous commercial aircraft variants, increased military demands, aerospace and other services, and already existing industrial and commercial titanium requirements, the projected titanium needs will exceed the worldwide production capacity in the near future. Cost and lead times (with near record commodity prices) have increased significantly. The 787 was a factor in this situation. The percent titanium used on the 787 is on the order of double that of prior commercial transports due to the compatibility of Ti with the graphite fibers in the carbon fiber reinforced graphite (CFRP) which is the primary material of construction of this aircraft, and its specific property advantages over aluminum and steel. Other new aviation requirements also contributing to this shortfall would be introduction of the F-35 fighter being built by Lockheed Martin, Northrop Grumman and BAe Systems, and the Airbus A-380 jumbo jet.

In addition to the obvious solution of increasing the capacity of the titanium industry, this situation has resulted in significantly accelerated studies of technologies which would reduce the buy:fly ratio (fabrication of more near-net shapes) and, ultimately, cost. Reducing the buy:fly would not only reduce cost due to reduced buy weights and machining, but, with procurement of less material it would also alleviate the anticipated supply shortfall. This involves studying technologies such as more near-net shaping, welding, single melt plate, improved machining and beta forging.

The Ti shortage has also accelerated the study of "low cost titanium". There are many new processes under varying stages of development1) to produce a lower cost Ti**,** with focus on producing powder, sponge or direct reduction and melting in a continuous process.

Most of the development efforts with titanium have been directed toward reducing cost. With regard to improved performance, programs directed at higher strength have been undertaken. These would include studies of Ti-5Al-5Mo-5V-3Cr and titanium matrix composites (TMC) including selective reinforcement with SiC fibers and boron reinforced nanocomposites.

2. Recent Developments

This section will cover technologies that have been implemented in the last few years, or implementation plans that are imminent.

2.1 Ti-6Al-4V - General

There are several developments/technologies related to Ti-6Al-4V (Ti-64) which will be discussed in this section. A rather mundane but significant development was the generation of "A" and "B" basis design allowables. Despite the many millions of kgs of Ti-64 used over the years, this design data was never formally developed. Designs have been premised on what is referred to as "S" or specification basis allowables, based on specification minimum values. The regulatory agencies, such as the FAA and JAA permitted this because of the extensive experience with the alloy with given applications. However, with the development of the Boeing 787 and the new types of applications driven by the use of composites, past history could not be used to justify its use with S basis allowables; A and B allowables were required.

2.2 Ti-6Al-4V - F-35 Applications

The F-35 or JSF program currently undergoing design development and demonstration is striving to achieve an optimum balance of structural concepts that consist of lethality, survivability, supportability, and affordability. These so-called program pillars significantly impact the airframe structural weight and cost in terms of the three F-35 variants. Structural weight and cost goals within the performance and affordability objectives are being satisfied by optimizing integral structures, sizing frame and bulkhead spacing, and employing state-of-the-art manufacturing processes. Materials selections and usage are typical of modern fighter aircraft structures, including polymeric composite materials, 2XXX and 7XXX Al alloy and Ti-6-4 product forms. The Ti-64 materials selections are based on fully mature and well characterized products utilized in previous military aircraft programs. Ti-6-4 die forgings and rolled plate are typically being employed in the beta annealed temper for durability and damage tolerance designed critical structures, and mill annealed temper for strength and stiffness driven design considerations. The typical materials selection mixture based on preliminary design decisions for JSF is given in DJC3. The materials mix for airframe structural materials selection for modern fighter systems, the F-22 and F-35 are illustrated in **Figure 1.** This figure demonstrates the importance of the aircraft mission on materials usage; the F-22 with its higher speed and more demanding mission uses more Ti.

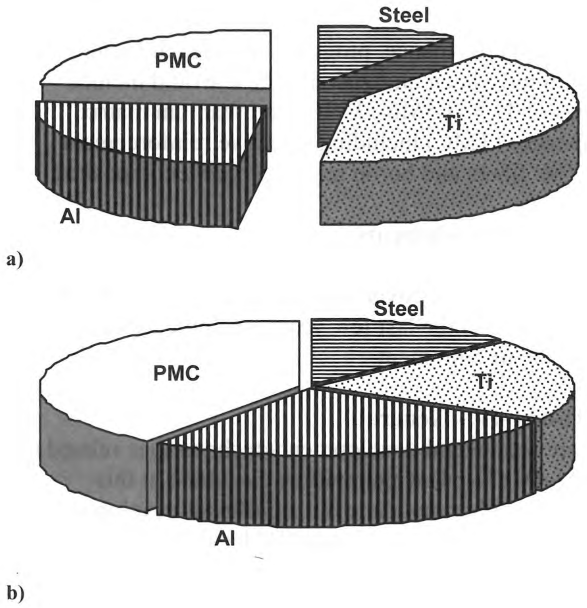

Figure 1. Structural materials mix for the a) F-22 and b) F-35 aircraft

2.3 Ti-6Al-4V — SPF and SPF/DB

Fine grained Ti-64 sheet, developed jointly by Boeing and VSMPO, is being used in the fabrication of SPF and SPF/DB components for hot structure on the 787. This material, with a primary a grain size of ~1µm offers significant fabrication advantages related to the ability to form at lower temperatures than that required for sheet procured per the industry specifications. The advantages associated with this include 1) reduced power requirements, 2) longer die life, 3) faster forming rate, 4) less thinning, and 5) reduced surface contamination, requiring an etch rather than a Chem mill$^{2)}$. Advantages associated with the reduced metal removal requirement would be improved dimensional control and less concern with excess hydrogen pickup. The reduced amount of thinning means that thinner gage starting material can be used so in addition to the cost savings obtained in forming these complex parts, providing further weight savings. Additional sources/alloys are also being investigated.

BAE Systems has advanced the state-of-the-art of production SPF/DB on the Typhoon (formerly referred to as the Eurofighter)$^{3)}$. In addition to the few dozen 2-sheet SPF parts they fabricate for this aircraft, they have also incorporated 4-sheet SPF/DB structure in the canards (the sheets are diffusion bonded first and then blown out to form the 'X' core type structure illustrated in **Figure 2).**

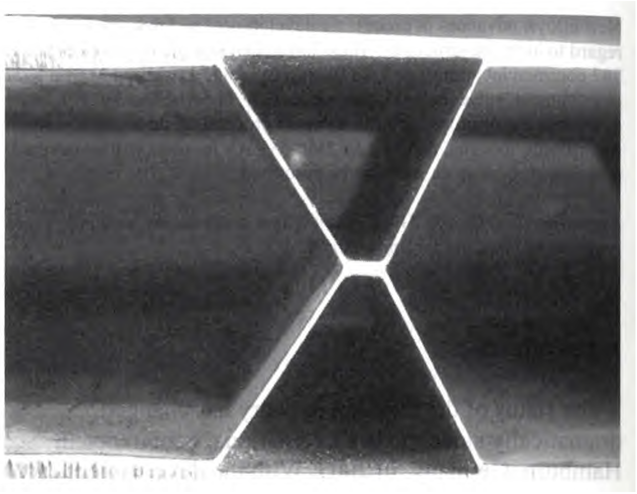

Figure 2. Segment of 4-sheet 'X' Core Configuration of SPF/DB Typhoon Foreplane or Canard. (Courtesy of BAE Systems)

To the authors' knowledge this is the first 4-sheet SPF/DB structure in production. Two-sheet SPF/DB structure is used for the keel of this aircraft. Their usage of SPF and SPF/DB was brought about by the reasons normally cited — reduced cost through reduced part and tooling counts and reduced assembly time in addition to the weight savings often associated with this type of structural concept. It is the most efficient method of fabricating thin gage complex structures.

2.4 Ti-6Al-4V Hearth Melting

All of the US suppliers are pursuing qualification for supplying Ti-64 plate which goes through a single cold hearth - electron beam (EB) or Plasma - melt cycle. (Qualification of plate would logically lead to other product forms, but the emphasis is on plate at this time.) All specifications for titanium alloys presently require following a hearth melt with a VAR cycle. It is felt by many that this VAR cycle is not value added. Some of the more important requirements for qualification of single melt plate would include demonstration of removal of high and low density defects, uniformity of chemistry, equivalent properties, and, for plate, a comparable texture to that of conventionally processed plate. The latter two items are particularly important as it is key to demonstrate that the single melt plate is equivalent to, or better than, the VAR product. This would enable direct substitution of the single melt plate where conventional plate is presently used, immediately providing a large market. Demonstrating chemistry uniformity is more of an issue with EB melting for two reasons related to the sublimation of the aluminum from the melt pool: 1) the Al content of the input stock must be enriched to account for the evaporation during melting; the magnitude of the loss will be related to the melt rate and other factors. 2) This evaporation then leads to the next problem. The vaporized Al will condense on the structure above the hearth. This condensate may fall back into the molten pool. The melters must demonstrate a method of handling this occurrence, particularly in the withdrawal pool. This situation could be mitigated by simply isolating and cropping that portion of the ingot, or proving that the condensate will be fully re-dissolved with resulting uniform aluminum chemistry. Through a USAF Metals Affordability Initiative — a Dual-Use Science & Technology program, an AMS specification, AMS 6945, and MMPDS-2 Design Allowables for static properties were generated and approved that encompass all three suppliers and both processes. The data indicated that a single hearth melted plate product is equivalent to that fabricated by conventional VAR melting[4-6)].

The equivalency of fatigue and fracture properties for military aircraft applications was also demonstrated on this program, and it has been approved and implemented. A partnership of Boeing, Spirit AeroStructures, Allvac, RTI, and Timet has completed static, durability and damage tolerance testing for Boeing Commercial Aircraft. Demonstration of equivalency to VAR melted plate will lead to release of a Boeing specification for commercial aircraft.

Lockheed Maritn Aeromautics (LMA) also participated as a development and evaluation partner in the single-melt Ti efforts, and is currently determining application opportunities on line-of-business and prototype aircraft programs. The benefits of the single-melt processes are greater scrap flexibility, lower processing costs, and higher yields of plate from melt stock due to their larger size and the fact they can be cast as rectilinear slabs. This should reduce the plate fabrication cost by something on the order of 10-20%. In addition, Ivasishin et al claim that it may be possible to eliminate the solidification texture[6].

2.5 Direct Metal Deposition

Another area of considerable interest has been metal additive manufacturing or direct metal deposition (DMD). Efforts continue in the fabrication of DMD Ti alloys, primarily Ti64 and Ti-6Al-2Sn-4Zr-2Mo (Ti6242), to yield near-net shape parts and to reduce part counts. Energy sources including laser, electron beam, and arc with both powder and wire feedstock have been processed and evaluated along with secondary post-processing parameters. One of the first commercial processes, Laser Additive Manufacturing (LAM)[7,8)], was qualified for flight hardware and is in service on a variety of DoD and NASA aircraft. Industry specifications have been released and are being updated, along with standardized qualification procedures. The primary near-term opportunity is for making components for short-run and prototype aircraft, where lead times and compressed design schedules do not allow for procurement of large forged block or die forgings. It is ideal for prototypeapplications in that no tooling is required. This also means that design changes would have minimal impact. Another opportunity is to make complex and unitized components that cannot be fabricated by conventional wrought and machining processes. The primary implementation challenges are deposition rate and distortion control. The deposition rate must be high enough to make the process economically viable; controlling the residual stresses is obviously important for maintaining dimensional control. The DMD technology does offer another potential advantage. By using different powders or wires in specific locations, components with tailored gradient microstructures and strength could be produced. For instance on a fitting with a lug, the lug is often the most highly loaded portion of the part. A higher strength feedstock could be blended in and utilized to fabricate the lug. This minimizes the cost by minimizing the amount of the higher cost higher strength alloy feedstock.

Comparisons of the microstructures and properties of Ti64 DMD Ti products have revealed some insightful trends in terms of processes and products. A slight decrease in static properties versus mill annealed plate, with equivalent durability, and superior damage tolerance characteristics has been observed. This is a result of the very fine Widmanstätten structure that comes from the high cooling rates. An example of the utilization of this technology is illustrated in Figure 3. This is a replacement part for a military aircraft. DMD was used while forging dies were being fabricated. Use of this technology enabled more rapid implementation of replacement of these parts. The fast turn-around in addition to the fact that no tooling is required offered technical and scheduling advantages.

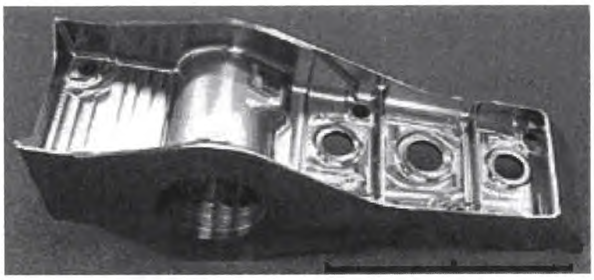

Figure 3. Fully machined LAM F-15 Pylon Rib (Courtesy DoD ManTech)

Another application of this technology would be weld repair. It would involve lower heat input than that of fusion welding with a microstructure that provides properties more comparable to that of the base metal than that of a fusion weld nugget.

DMD or additive manufacturing processes are being considered for use on limited production or prototype aircraft systems, where design flexibility, schedule constraints, and affordability issues are not consistent with the incumbent wrought Ti alloy products.

2.6 Ti-6Al-4V Castings/Forgings

The F22 Air Dominance Fighter was the first high performance aircraft to use large titanium castings in fracture critical applications[9]. This included the wing side-of-body joint which mated the wing to the fuselage. Since the last international conference, there have been significant changes to the casting use on the F22. The side-of-body joint and aileron castings, two of the largest on the aircraft, have been converted to welded assemblies made from machined forgings and plate.

Titanium castings hold significant potential for cost and weight savings, when properly used. In the case of the F22 Side-of-Body castings, costs increased due to a significant non-destructive inspection burden that was not understood or accounted for early in the design phase. Attempts to lower stresses in critical locations by increasing cross-sectional area exacerbated both fabrication process and NDI issues and lead to weight growth in the structure.

The above concerns ultimately lead to a design change to a multi-forging EB welded assembly. This approach ended up being lower cost and 50 kg (110 lb) lighter than the titanium castings they replaced.

In addition, advances in machining technology now make fabrication of single piece side-of-body joints technically feasible and affordable. Though more costly than the welded assemblies, the single piece option does not add any additional weight and is now used as an alternate to the welded assembly.

Castings will continue to be beneficial for applications that take into account the unique aspects of that fabrication method. Some of the lessons learned from the F22 program included, designing with NDI in mind, particularly keeping radiographic inspection thicknesses to under 5 cm (2 inches) and accounting for dimensional distortion, particularly at the intersection of thin and thick details. Other process requirements were previously detailed by Phelps et al[10].

2.7 Ti-10V-2Fe-3Al

The Airbus A-380 utilized Ti-10V-2Fe-3Al (Ti1023) for landing gear structure for applications similar to that of the Boeing 777. These applications, as with other applications of the alloy are premised on weight reduction in comparison to the high strength steel it replaces **(Figure 4).** A further advantage of the use of titanium for the landing gear is reduced maintenance costs. The steel landing gear requires costly, time consuming refurbishment every 7-10 years. Use of titanium eliminates this sustainment requirement.

2.8 Ti-5Al-5Mo-5V-3Cr

There has been a lot of activity with this alloy in the US and abroad with the goal of improved performance —reduced weight. The alloy is being studied at Boeing in three product forms — forgings, plate and castings — and is used at two strength levels. The high strength STA condition has a minimum ultimate tensile strength (UTS) of 1240 MPa (180 ksi)[11,12]. This condition is presently used for landing gear components. The 787 landing gear uses Ti5553 for parts similar to the Ti1023 parts used on the Boeing 777[13] and the Airbus A-380 (figure). These applications replace a high strength low alloy (HSLA) steel, 4340M, which is used at the 1930 MPa (280 ksi) UTS strength level. The titanium provides weight savings with reduced maintenance for the airlines.

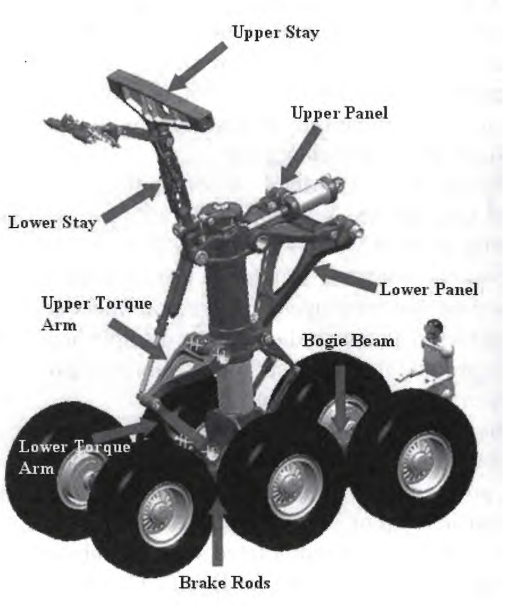

Figure 4. Airbus A-380 landing gear. The labeled parts are the Ti-10V-2Fe-3Al components.

An alternate, lower strength, heat treatment has also been developed for a higher strength alternative to Ti64 but with improved damage tolerance properties relative to Ti5553 or other high strength alloys in the STA condition. This heat treatment is referred to as the beta anneal, slow cool and age (BASCA) condition. The minimum UTS is 1100 MPa (160 ksi) with a minimum fracture toughness of 72 MPa√m (65 ksi√in). The forging properties are similar to those obtained with investment castings14). Anticipated use for this condition would be primarily for wing and nacelle structures.

Casting applications for this alloy are being considered for nacelle applications as a means of reducing cost through casting a near-net shape. Casting characteristics and properties have been described elsewhere[14] and appear to be comparable to those of forgings. Ti5553 plate in the BASCA condition is also being assessed. Plate could be used in fabricating complex components via weldments to reduce the buy:fly ratio.

A joint program between Alcoa Fastening Systems and TIMET developed high strength Ti5553 fasteners, referred to as AEROLITE®, capable of a 1240 MPa (180 ksi) minimum tensile strength and (108 ksi) minimum shear strength. For comparison, Ti-64 fasteners up to 19 mm (0. 75 in.) dia. are capable of minimums of 1105 MPa (160 ksi) and 655 MPa (95 ksi), respectively. The AEROLITE® fasteners also exceed the fatigue requirements of the steel fasteners which they are intended to replace[15]. Thread rolling has been an issue with many high strength fasteners. They must be rolled in the fully heat treated condition and this has often resulted in laps and cracks in the threads or excessive shear bands. This was not an issue with the AEROLITE® Ti5553 fasteners.

2.9 Welding

Advanced joining efforts continue for the full spectrum of aerospace Ti alloys, with the objectives of improving joint efficiencies, reducing variability, and contributing to manufacturing cost reductions in large components. Advances have occurred in both fusion and friction welding processes. Both EWI[16] and TWI[17] have reported success in friction stir welding of titanium alloys. Linear friction welding has been developed for aero-engine applications, greatly reducing weight and cost[17]. Reduced pressure electron beam welding, originally developed by TWI for offshore oil applications, has demonstrated the capability to produce aerospace quality welds. All of these weld technologies are being studied for airframe applications to fabricate more monolithic structure yielding reduced cost and weight.

2.10 Machining

With the increased usage of thick section plate and forged Ti-6-4 alloy products, efforts to understand and improve the machining behavior of Ti products has been undertaken. Simulation and modeling efforts have included tool design, coolants, process parameters, and other factors, to improve cycle times and surface quality of machined Ti alloy components. With improvements in machining parameters and warpage issues, further enhancements are available to the design and analysis communities in terms of thin section and integral piece parts. Typical sustained rough machining rates in the 1980s were 300 mm^3/sec (1in^3/min), and typical sustained finish machining rates were 3 mm^3/sec (0.01in^3/min). Current rates are 1200mm^3/sec (4in^3/min) for roughing and 300mm^3/sec (1in^3/min) for finishing. This has been achieved by improved techniques, cutter geometries, and materials, with tool life remaining at 1 change per hour. Minimum web and flange/stiffener thicknesses were 2.5mm (0.1in), and are now as low as 1mm (0.04in), while corner radii have been reduced from 1/4 the pocket depth to 1/8 the pocket depth.

Very significant gains have been made in the last 20-30 years in terms of machining speeds. These gains have been achieved via improved tool design, materials and machining techniques. In terms of rough machining the metal removal rates have increased by a factor of 4 since the 1980's, while they have improved up to 100-fold for finish machining rates[18]. Techniques have also been developed to enable machining to thinner gages without distortion and deeper pockets with smaller fillet radii.

2.11 Titanium Matrix Composites

Design and fabrication interest in titanium matrix composites (TMC), both continuously and discontinuously reinforced, has been ongoing to exploit high specific stiffness and strength for weight critical aerospace applications, such as landing gear and other axially loaded structures. While significant weight savings can be gained with this technology, cost has always limited its usage. Boeing and LMA have been conducting trade studies for potential applications for landing gear structure with continuous fiber reinforcement[8]; in the final analysis, though, the cost per kg of weight saved was deemed too high. On the positive side, General Electric has put this technology into production on exhaust nozzle links and thousands of them have been produced[8].

SP Aerospace, a Dutch firm, has reported they have flown the first airframe landing gear TMC part, a prototype lower drag brace for a Dutch Air Force F-16. The TMC consisted of a selectively reinforced Ti-6Al-2Sn-4Zr-2Mo matrix using Textron SiC SCS-6 fibers. Taxi and flight tests confirmed the TMC design performed as anticipated[19] and is illustrated in Figure 5. Use of the TMC for this application, as a prototype (i.e., low volume production), was about 4000 euros/kg ($2000/lb). While it is anticipated that costs of this nature will have very limited applications, programs of this nature are necessary to further develop the technology and, ultimately, reduce the cost.

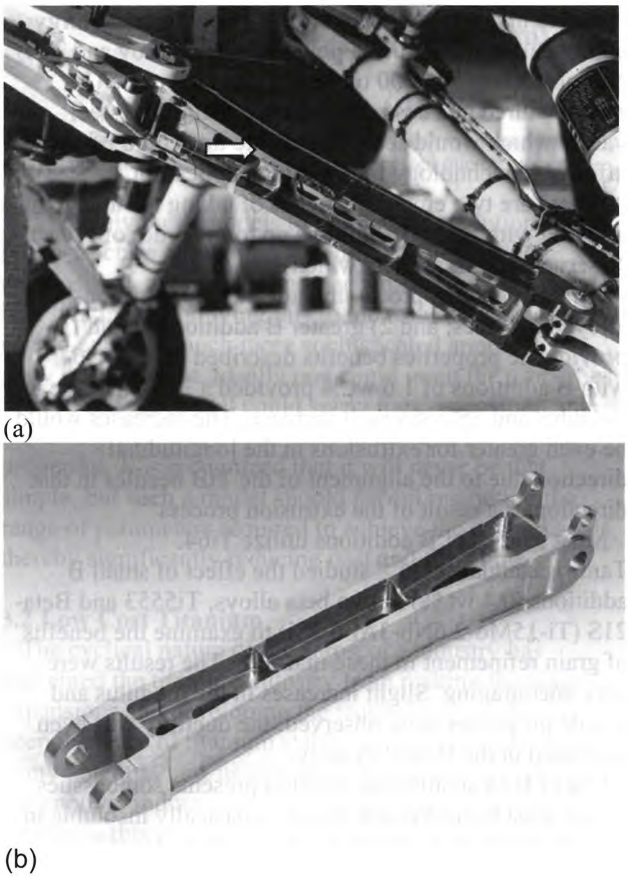

Figure 5. Selectively reinforced prototype F-16 landing gear lower drag brace. a) as installed on the F-16; b) machined part.

There has also been a lot of activity with discontinuously reinforced composites with additions such as B or C which result in intermetallic particles with high hardness and stiffness[20-22]. They are sometimes referred to as nano-composites as the TiB particles, when properly processed, will be in this size range. These metal matrix composites have been purported to offer advantages in terms of thermal and thermomechanical processing (improving product yield with minor additions), and increased stiffness, tensile strength, elevated temperature capability and wear resistance with higher additions. TiB composites are in production in the industrial and automotive sectors. TiB would seem to be an excellent particulate reinforcement for Ti in that it is chemically compatible with Ti, serves as a strong grain refiner, and the density and coefficient of thermal expansion are comparable with the titanium alloy matrix[20]. The most significant application to date is for intake and exhaust valves for the Toyota Altezza engine. This application was driven by the increased stiffness, strength and wear resistance offered via the B in a Ti64 matrix for the intake valves and Ti-6.5Al-4.6Sn-4.6Zr-1Nb-lMo-0.3Si for the exhaust valves[23]. These components were fabricated using a powder metallurgy approach, with hydride Ti powder, master alloy and TiB$_2$ particles. Over 500,000 of these valves have been manufactured at a cost about double that of the steel valves which would seem to indicate this could be a cost affordable technology for the right application. There are two emerging means of taking advantage of alloying with B; 1) B additions up to the order of 0.1 wt. % serve as grain refiners which may offer thermomechanical processing advantages over non-B alloyed matrices; and 2) greater B additions would provide the properties benefits described above. Ti64 with B additions of 1.6 wt % provided a 24% increase in modulus and 35% strength increase. The increases would be even greater for extrusions in the longitudinal direction due to the alignment of the TiB needles in that direction as a result of the extrusion process [20].

Most studies of B additions utilize Ti64. Tamirisakandala et al[22] studied the effect of small B additions (0.1 wt %) in two beta alloys, Ti5553 and Beta-21S (Ti-15Mo-2.6Nb-3Al-0.2Si) to examine the benefits of grain refinement in these matrices. The results were very encouraging. Slight increases in the modulus and tensile properties were observed; the ductility was even increased in the Beta-21S alloy.

Use of B as an alloying addition presents some issues which must be addressed. Boron is basically insoluble in Ti so the formation of TiB needles or particles is inevitable and provides the properties benefits described above. Ingots containing B additions have successfully been cast, but only in small sizes. Controlling the size and distribution of these intermetallic particles and preventing agglomeration of the B containing particles would be more of an issue with larger ingots which will be required to be economically viable on a production basis. Because of this factor, control of the scrap stream will be important to assure that B containing scrap is not inadvertently introduced into an ingot where the special melt controls required are not followed.

The required melting controls and the difficulties in maintaining a fine uniform distribution in a large ingot would seem to be very difficult. Therefore, the authors consider that the best opportunity to implement this technology is a solid-state, meltless, powder metallurgy approach. It is much easier to control the particle distribution in powder particles — they can never be larger than the particles — when melting is not required. It would also seem to simplify attaining a uniform distribution. The control of the size and distribution of the particles is felt to be very important to the properties, and the uniformity of these properties. These factors will also be very important to the ductility in addition to the other properties. A large local concentration of particles in a local region, or agglomeration, could result in a local ductility loss and premature failure under static load conditions. Similarly, in a fatigue design it is felt that the lower ductility will result in a premature fatigue failure in the presence of a geometrical stress intensity, such as at a fastener hole.

Powder metallurgy and DMD would seem to provide another means of retaining a fine particle size. Use of powder feedstock permits novel material additions such as erbium, boron, and other compound forming elements. With laser deposition these materials can be incorporated into a fine, homogeneous distribution of second phase particles. Figure 6 shows an example of this type of structure. This micrograph shows commercially pure titanium with one percent boron after laser powder deposition. The resultant boride precipitates are nanoscale and homogeneously dispersed. This small addition resulted in a 230% increase in the tensile strength versus unmodified CP-Ti while still maintaining 12% tensile elongation. By taking this concept and applying it to more heavily alloyed base materials (such as Ti-64) and incorporating multiple novel alloy additions, much greater property enhancements are expected.

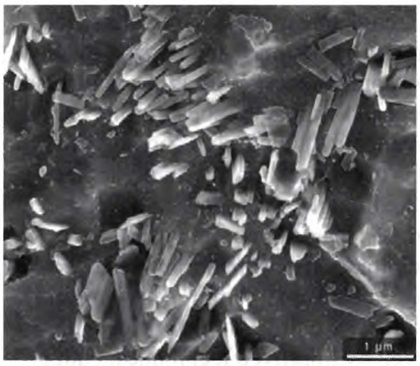

Figure 6. Fine scale microstructural features generated by laser deposition of Ti-1.0 pct. B alloys.

3. New Emerging Developments/Trends

3.1 Modeling

Application of computer-based modeling and simulation tools are now becoming more than an academic curiosity. Computer modeling and simulation of titanium materials and manufacturing methods are starting to emerge and support production component design optimization efforts[24].

Modeling of phase equilibria has become a mature field of science and engineering. Thermodynamic modeling is reaching many engineering applications. Casting modeling simulations utilize thermodynamic modeling tools and databases to allow accurate prediction of solidification paths. These modeling and simulation tools are allowing the prediction of porosity and segregation within a wide range of commercial alloys. Thermodynamic and solidification modeling efforts have shown that modest amounts of residual elements, such as iron, in commercial alloys will greatly increase the solidification range[25].

Deformation modeling tools have become commonplace in aerospace forging manufacture[26]. In addition to simulation of bulk metal deformation, efforts are being undertaken to model the evolution of microstructure. Methods for the conversion of titanium ingots into refined billet material, and slab stock into refined plate and sheet material are being optimized based on modeling and simulation tools[27]. Diffusion-based mechanistic models have been applied to alpha phase growth[28]. Phase-field models have been developed and applied to grain boundary alpha growth, beta grain growth and acicular alpha precipitation and growth[29].

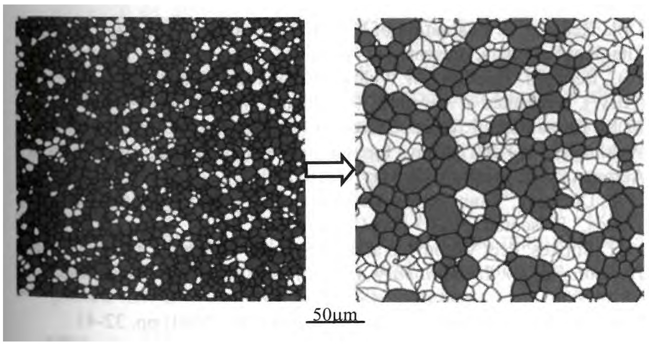

Figure 7. Phase field prediction results for beta grain growth. The average beta grain size grew from 55 to 130 μm in 90 seconds at 1000°C.

Figure 7 illustrates the results of a beta grain growth model. These results compared favorably with a laboratory heat treatment study. It was determined that the crystallographic texture was important in this determination. The results assuming a random texture did not compare favorably with laboratory results. The texture, and its influence on grain boundary mobility were key to getting an accurate model. In addition to computer simulation of microstructure evolution, efforts to allow prediction of mechanical properties based on chemistry, manufacturing methods and microstructure are being developed[30]. Tensile, fracture toughness and fatigue models are continuing to evolve to allow industrial application to component and process design optimization efforts. **Figure 8** demonstrates the neural net prediction of tensile strength vs alpha lath width based on tensile properties achieved via a range of heat treatments which affect the alpha lath width. The accuracy diminishes toward the high end of alpha lath widths as there is less data in this region.

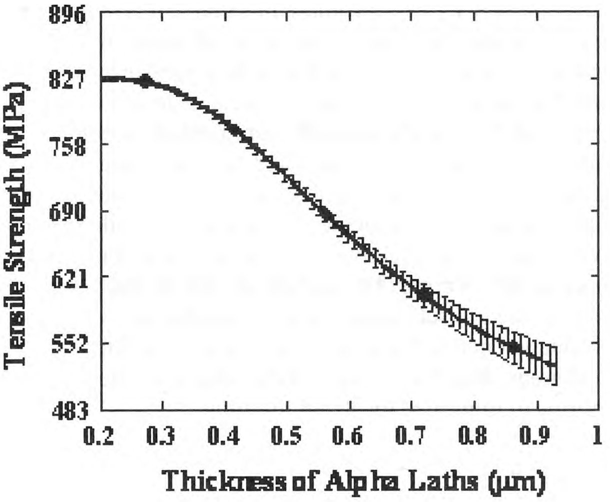

Figure 8. Predicted relationship between alpha lath width and room temperature tensile strength in Ti64 beta processed microstructures

Ultimately these models to predict the evolution of the microstructure taking into account the chemical composition, texture, thermomechanical processing and heat treatment, and tying this to the resultant properties should enable a much more sophisticated approach to alloy development. Ideally one could input the properties desired and the model could select the composition and required processing of the alloy to achieve the desired properties. It is recognized that it will never be that simple, but such a model should permit restricting the range of parameters required to achieve the desired goals, thereby significantly reducing cost and flow time.

3.2 Low Cost Titanium

The cyclical nature of the aerospace industry has prevented the titanium industry from making the plant expansions and developing the technologies needed to keep the price of titanium stable and low. This has kept many potential new users out of the market, including automotive, industrial, naval, and ground vehicles. Changing this cost picture has been the objective of the DARPA titanium initiative, which has a goal of getting the cost of mill product down to $13/kg, which is similar to austenitic stainless steel on a per-volume basis, and half the cost on a per MPa basis. Many low cost titanium processes are being studied all over the world[1]. However, only the Armstrong[31] and MER[32] processes are moving into scale-up in the near term, with significant quantities from both processes expected in 2008. Research in solid-state consolidation of both blended elemental and prealloyed powders by DARPA and the Army, are leading towards making the cost goal a near-term reality.

3.3 Laser Induced Superplasticity

A very innovative means of superplastic forming and superplastic forming/diffusion bonding is being developed in a collaborative effort between the University of the West of England and the University of Central Florida. They have formed a company LISTechnology Ltd to promote this concept. The parts to be formed are placed in a pressurized chamber with a ceramic die mold. The chamber is then pressurized to push the material into the die; the heat source is a laser beam which is programmed to incrementally form the part. It is anticipated that they will be able to use this for titanium, aluminum and nickel based alloys. Laboratory experiments to date indicate the technology could provide a very rapid, cost effective and energy efficient method of superplastic forming. The energy savings in not having to heat the die in itself would be very significant. Another advantage cited is the possibility of reducing thinning in local areas. The heat source can be played on the part as it forms to minimize localized thinning.

This technology is still in a very early stage of development but if it is proven out, it would seem to offer the potential to produce complex sheet metal parts in a cost effective manner.

4. Summary

The research and development efforts over the last 4 years have probably been more intense than ever before. Due to the increased demand in the aerospace industry costs have increased significantly and lead times have been extended. Consequently a very significant effort has gone into reducing cost and material requirements via avenues such as developing technologies to reduce the buy:fly ratio, increasing machining speeds and direct metal deposition. It also appears that lower cost titanium is on the horizon through improved titanium ore reduction techniques. Another technology which should reduce the time of bringing new materials to the market place is the development of simulation and modeling techniques.

Significant strides have been made in these technical arenas. There is also ongoing work for improved performance. The most obvious manifestation of this is the use of titanium for significant landing gear applications on the Airbus A-380 and Boeing 787. A lower strength, more damage tolerant version of Ti-5Al-5Mo-5V-3Cr is being developed for other applications. Metal matrix composites are still being studied, but as stated many times before, cost is often limiting their applications.

The trend with new aircraft structures seems to be for increased usage of carbon fiber reinforced plastics. This increases the amount of titanium usage so it would appear that the trend for increased titanium usage will continue into the foreseeable future.

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