Titanium Aluminides for Aerospace Applications

J.C. Chesnutt

GE Aircraft Engines
One Neumann Way, MD M89
Cincinnati, Ohio, USA 45212-6301

Abstract

The U. S. aircraft industry has realized much of its success because of the steady improvements in specific thrust (thrust/weight) and in specific fuel consumption (fuel used/unit of thrust). The desire to further improve specific thrust both for IHPTET (Integrated High Performance Turbine Engine Technology) and NASP (National Aerospace Plane) programs in the U.S. and similar programs abroad, has led to extensive research and development of titanium aluminides (alloys based on the intermetallic compounds Ti_3Al and TiAl) in the last five years. This article will review some of the progress made in developing these alloys and will comment on their potential for advanced engine applications in the near future.

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Introduction

The application of titanium aluminides will be driven by the commitment to high performance (specific thrust) and will be led by the application in demonstrator engines, such as those planned for the IHPTET (1,2) program. This commitment to high performance places focus on both the light weight and higher temperature capabilities of titanium aluminides. Application will, most likely, be driven by the trade-off necessary to achieve a balance of properties for a given application, a balance that is more difficult to achieve with these alloys of limited ductility and toughness. The IHPTET goal of a 2X improvement in specific thrust has provided major impetus for development of the titanium aluminides. Monolithic gamma titanium aluminides and titanium aluminide based metallic matrix composites are on GE Aircraft Engines' list of top priority IHPTET materials. The titanium aluminides offer advantages of high modulus, low density, elevated temperature strength and creep resistance. Some of the development and production issues that must be addressed, if successful application of titanium aluminides is to be achieved, are lack of low temperature ductility and toughness, producibility and fabricability, and cost. The advantages of and issues associated with titanium aluminides will be discussed in terms of their properties, processing to produce material and components, planned applications and engine test experience.

Properties

A simple comparison of titanium aluminide alloys with conventional titanium-base and nickel-base alloys is shown in Table I.

Table I - Comparison of Titanium Aluminides with Titanium Alloys and Superalloys

Property	Ti Alloys	Alpha-2	Gamma	Superalloys
Density, g/cm^3	4.54	4.84	4.04	8.3
Stiffness, GPa	110	145	176	207
Max T - Creep, °C	540	730	900	1090
Max T - Oxidation, °C	590	705	815	1090
Ductility - Room T, %	15	2-4	1-3	3-10
Ductility - Oper. T, %	15	5-12	5-12	10-20

The two titanium aluminide alloy classes will be referred to as alpha-2 alloys and gamma alloys in the remainder of the article. Generally, for alloys of interest for advanced engine applications, the former comprises a mixture of alpha-2 and beta phases, and the latter a mixture of gamma and alpha-2 phases. More detailed discussions of properties of "first generation" alpha-2 and gamma alloys can be found in several recent articles (3-5). Extensive research and development on these alloys have been conducted at GE, both at Aircraft Engines and at the Corporate Research and Development Center. Highlights of typical properties recently achieved in alloys developed at GE are shown in Table II.

Table II - Recent Property Highlights

Alpha-2	Gamma
1,100 MPa UTS with 2-3 % tensile ductility at room temperature	620 MPa UTS with 3 % tensile ductility at room temperature
Up to 6% tensile ductility at room temperature	550 MPa UTS at 760°C; 380 MPa UTS at 870°C
620 MPa UTS at 760°C	Excellent oxidation resistance
Good HCF for $K_t = 1$	More fire resistant than conventional titanium alloys
Good oxidation resistance	

The challenge of designing with titanium aluminides includes a need to deal with their lack of low temperature ductility and toughness, and fatigue crack growth characteristics (damage tolerance). In addition, sufficient design data does not exist due to the absence of a "standard" first generation material. Finally, those alloys that are most suitable for advanced design, that is those with improved properties, are generally not well characterized. Like conventional titanium alloys, the titanium aluminides have exhibited a strong relationship between processing, microstructure and mechanical properties. There is, therefore, a strong need for developing and improving the processes necessary to produce and fabricate these alloys, concurrent with developing the design data base that will enable successful application of the alloys.

Two alloys that have received considerable attention at GEAE are the alpha-2/beta alloy, Ti-24.5Al-12.5Nb-1.5Mo (at %), and the gamma/alpha-2 alloy, Ti-48Al-2Cr-2Nb (at %).

Alpha-2

The alpha-2 alloy has been developed by Marquardt and co-workers, and an extensive study of microstructure/property relationships conducted. The alloy composition resulted from research to produce an alpha-2 alloys with high fracture toughness coupled with adequate high temperature properties [6, 7]. Marquardt recently characterized the behavior of the alloy in 1) a beta forged and 2) an alpha-2 plus beta forged plus heat treated condition in which the volume fraction of primary alpha-2 was varied from 0 to 12 percent [8]. His results indicated that the volume fraction of primary alpha-2 has a strong effect on steady-state creep rate as shown in Figure 1.

Gamma

Early in the development cycle for Ti-48Al-2Cr-2Nb at GEAE, three microstructural conditions were identified as being of interest. These previously have been referred to as duplex (DP), sub-transus (ST), and fully-transformed (FT). Details of the heat treatments utilized to obtain two of these structures, DP and FT, have been reported by Shih, et al. [9]. A third microstructure studied has been referred to as the sub-transus microstructure. This microstructure is obtained by holding the alloy at a temperature slightly below the alpha transus and cooling from that temperature. That microstructure comprises a small volume fraction of primary gamma and a large fraction of lamellar (alpha-2 and gamma) structure. Examples of the three microstructures are shown in Fig. 2.

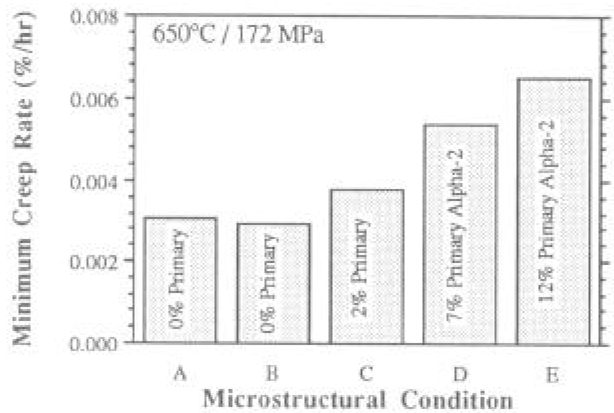

Figure 1 - The steady-state creep rate of Ti-24.5Al-12.5Nb-1.5Mo as a function of microstructure (volume fraction of primary alpha-2).

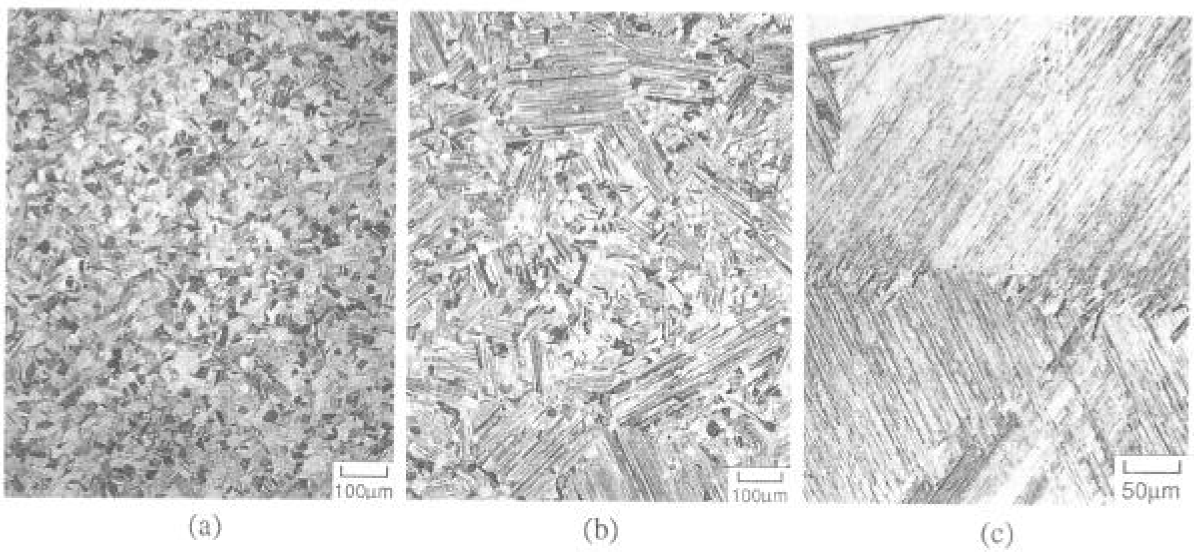

Figure 2. Representative microstructures of Ti-48Al-2Cr-2Nb. (a) Duplex, (b) Sub-Transus, and (c) Fully-Transformed.

Extensive mechanical property characterizations of the numerous microstructural conditions produced from extrusions and forgings has been conducted. In the following section, the tensile properties for a high extrusion ratio (20:1) extrusion will be compared with data from one of the large scale forging. Tensile and creep properties for the alloy in both a duplex and fully-transformed microstructural condition are shown in Figs. 3 and 4.

It can be seen from Figs. 3 and 4 that the duplex microstructure provides a good combination of strength and ductility, but does so at the expense of creep strength. The sub-transus microstructure provides a compromise between the duplex and fully transformed microstructures, in that the creep strength is intermediate to that of the duplex and fully transformed microstructures, and the tensile ductility is generally greater than 2 percent.

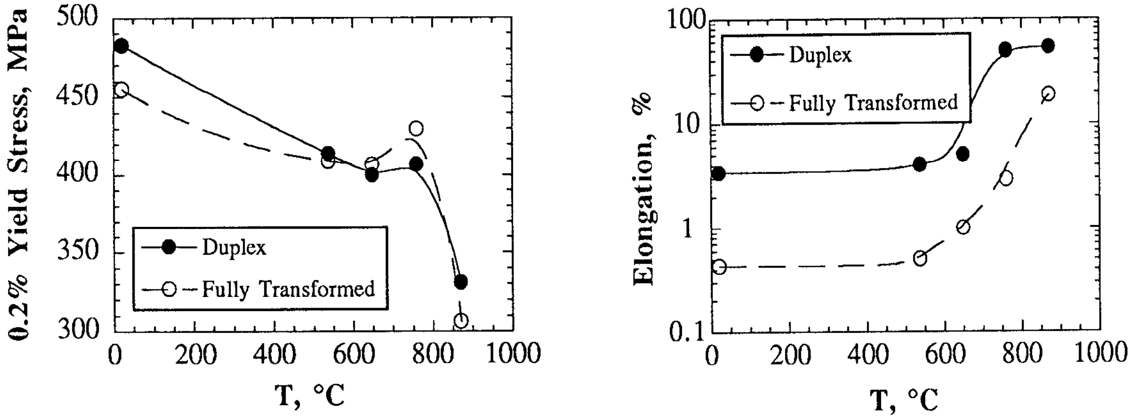

Figure 3. Tensile properties as a function of temperature for extruded Ti-48Al-2Cr-2Nb.

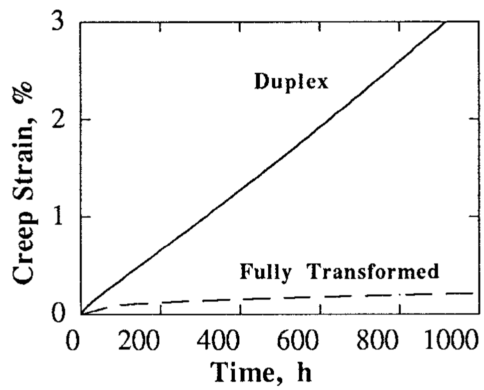

Figure 4. Creep of extruded Ti-48Al-2Cr-2Nb at 760°C and 103 MPa.

Processing

Considerable process development has occurred in the past five years. An assessment of the status and usefulness of various processing methods for titanium aluminides is shown in Table III.

Table III: Status of Processing Capability

	Ingot Metallurgy	Forging	Sheet Rolling	Casting
Conv Ti	Yes	Yes	Yes	Yes
Alpha-2	Yes	Yes	Yes, with difficulty	Limited
Gamma	Yes, with difficulty	Yes, with difficulty	Yes, with difficulty	Yes

Alpha-2 alloys are being produced in ingots of up to 3200 kg. Ingot conversion to billet requires special care, but once the alloy is at the billet stage, it can be processed in a manner similar to conventional alpha-beta alloys. Gamma alloys, by virtue of their relatively high ductile to brittle transition temperature, require working at high temperatures which are outside the range of conventional titanium processing equipment. To date this has limited the practical ingot size to 200 kg. Additional information on recent processing studies on Ti-48Al-2Cr-2Nb can be found in reference 10. The challenges for wrought processing of gamma alloys in large shapes has led to considerable interest in casting and powder metallurgy as alternate approaches to component fabrication. Examples of cast gamma components will be shown in a later section. The benefit of powder metallurgy has not been clearly demonstrated, and cost and quality of powders continues to be an issue.

Although metal matrix composites of the titanium aluminides are the topic of another paper in this conference, one GEAE perspective for these materials is as follows. Metal matrix composites fabricated from titanium aluminides offer additional benefit in terms of specific strength, specific stiffness, and toughness, and are being considered for advanced engine applications. Two leading candidate processing methods for titanium aluminide MMC's are: foil-fiber-foil fabrication and induction plasma spray (IPD) fabrication. Both processes have advantages and limitations and the choice may be strongly influenced by the component being fabricated. In addition, foil-fiber-foil fabrication is limited to those alloys that can be produced in sheet and foil gages. To date, only alpha-2 alloys have been produced in large (92 cm x 240 cm) sheet; production of alpha-2 sheet requires pack rolling as does conventional alpha-beta alloys. It is likely that for MMC's based on the intermetallic compounds, such as the titanium aluminides, IPD will be a fabrication method of choice on the basis of cost and ease of fabrication. MMC's are still very costly and will in all likelihood remain so until production quantities are available. Initial applications of titanium aluminides in the monolithic or reinforced form will be limited until property concerns are addressed and processing costs are reduced significantly.

Applications

Initial feasibility demonstrations of these alloys in air-breathing, conventional fuel engines are planned for IHPTET engines. Several candidate components for application of monolithic titanium aluminides are shown schematically in Figure 5.

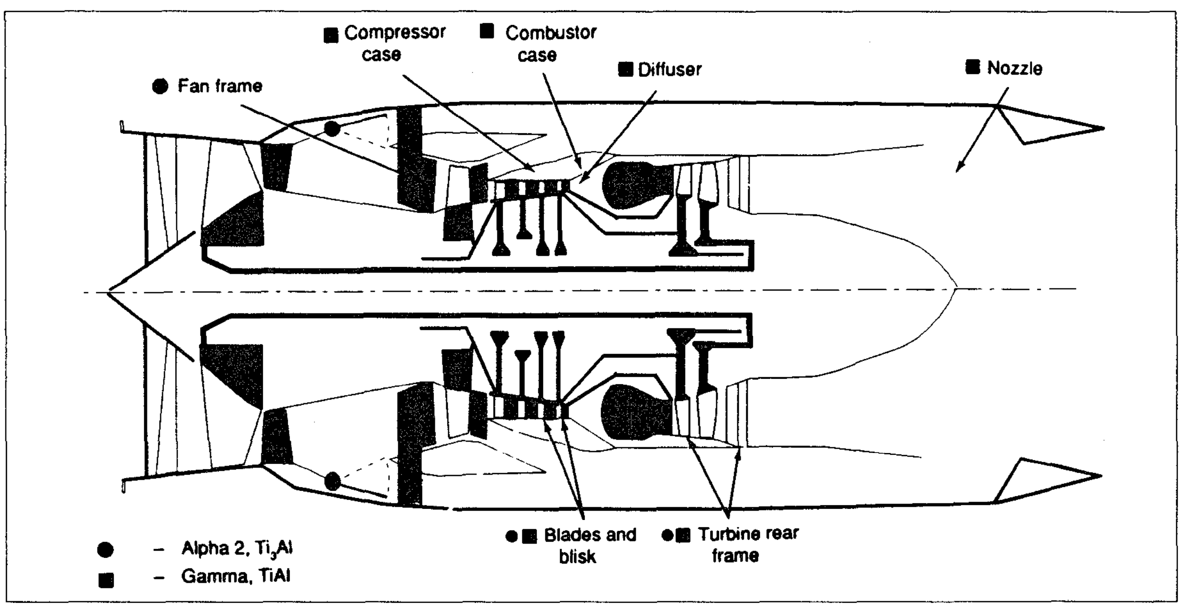

Figure 5 - Potential applications for monolithic titanium aluminides.

Fabrication techniques have been demonstrated for several of these components. These include the alpha-2 airfoil forging (Figure 6), a cast gamma airfoil (Figure 7), and a cast gamma compressor case (Figure 8).

Figure 6 - Alpha-2 airfoil forging

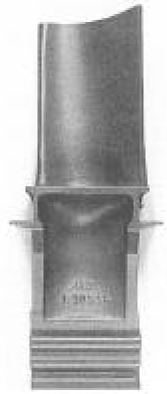

Figure 7 - Cast gamma CF6 1st stage turbine blade

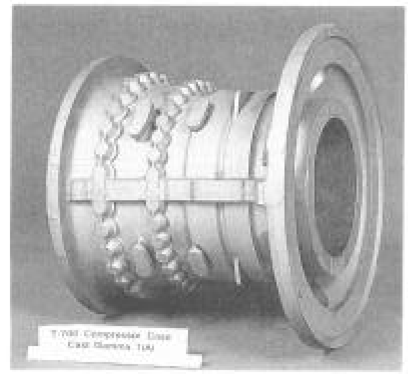

Figure 8 - Cast gamma T700 compressor case

These demonstrations have increased our confidence that components can be fabricated. Secondary fabrication techniques such as machining and joining have also been developed, with techniques for alpha-2 alloys being the most mature. Examples of two parts that were fabricated from an alpha-2 alloy and subsequently engine tested are given in the following section.

Engine Test

Several components have been fabricated from an alpha-2 alloy and engine tested at GEAE. Two of the components fabricated from the alpha-2 alloy Ti-24Al-11Nb (at %) are shown in Figures 9 and 10.

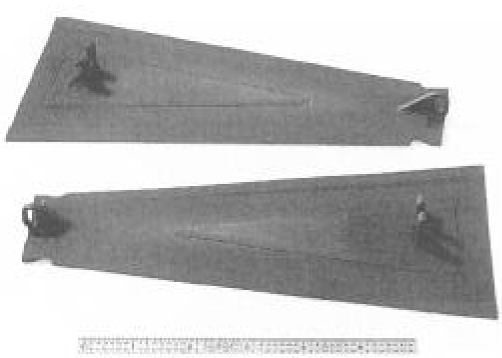

Figure 9 - Alpha-2 F404 primary exhaust seal.

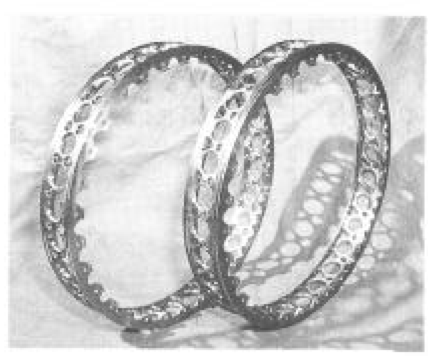

Figure 10 - Alpha-2 GE29 high pressure turbine support ring fabricated from alpha-2(left) and René 41(right).

The first component, Figure 9, is a F404 primary exhaust seal that was produced by superplastic forming and diffusion bonding. Two seals were engine tested for 97 hours operation (67 hours endurance) after which two after-burner (A/B) cycles were tried. During the second A/B cycle, one seal cracked at the front clevis and testing of these components was discontinued. The second component, shown in Figure 10, is a GE29 high pressure turbine support which was fabricated from a rolled ring. The component and a high pressure support cone both ran successfully for 100 hours. It should be noted that these components were tested prior to development of improved, "second generation" alpha-2 alloys that have higher strength and environmental resistance.

Summary

Extensive progress and improvements in titanium aluminides have been made in the last five years. This progress enhances the considerable potential for demonstration of these materials, both in monolithic and MMC form, in IHPTET engines and for future application in advanced military engines. Component shapes are producible and the vendor base is expanding and is becoming more experienced. It is clear that production applications will require production material sources at reasonable cost, and that excessive cost can kill the application of otherwise excellent technology. The transition of these materials from demonstration engines to production military engines will be more difficult than it has been for the more conventional alloys in the past. In addition, a much more extensive experience base will be required before these alloys can ever be considered for commercial engine applications. Finally, innovative designs will be required to utilize these materials with unique properties; unimaginative designs can reduce the payoff of new materials to an unacceptable level.

Acknowledgments

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