The Use of Cast Ti-48Al-2Cr-2Nb in Jet Engines

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Although it has been recognized for almost three decades that titanium-aluminide systems have the potential for significant weight reductions in jet engines, Ti-48Al-2Cr-2Nb has emerged as the first to enter commercial jet engine service. Cast gamma titanium aluminides are evolving from an intriguing idea into the next materials revolution for aircraft engines. Its potential appears to be similar to the changes caused by the introduction of cast titanium alloys in the 1970s.

INTRODUCTION

Approximately 30 years ago, the U.S. Air Force recognized that titanium-aluminide (TiAl) systems offered great potential for weight savings in the hot sections of jet engines. Since then, gamma titanium aluminides have emerged from the group of wide-composition intermetallic compounds as the first to enter commercial jet engine service.

Gamma alloys are a mixture of two aluminides, gamma $L1_0$, alpha-two DO_{19}, and, frequently, a small amount of B2. Because they are wide-composition intermetallic compounds, alloying elements can be added to alter their properties. Mn, Cr, Nb, Ta, V, C, and B have been added to the gamma TiAl base to improve ductility and toughness, while maintaining the high modulus and creep resistance of the gamma system. Ti-48Al-2Cr-2Nb (Ti-48-2-2), developed by S.C. Huang[1] of the General Electric Corporate Research Center, offers one of the best combinations of ductility, toughness, and creep resistance.

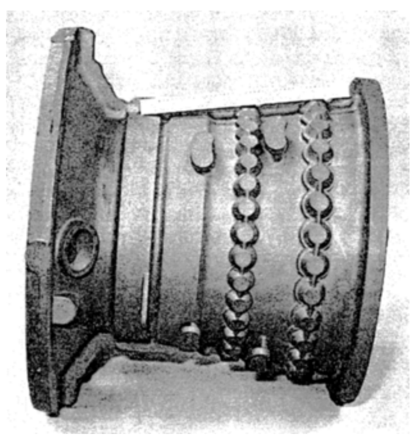


Figure 1. A cast T700 Ti-48-2-2 compressor case.

During the late 1980s, several alloys were being examined, mainly in Japan, for potential investment-cast applications. In the United States, Precision Castparts, Howmet, and Tiline all demonstrated shapemaking capability with Ti-48-2-2, producing castings similar in complexity to the T700 compressor case (Figure 1). This initial success showed the potential of the gamma alloys for near-net-shape casting; however, many problems remained, including cost of the alloy, affordable heat treatments, weldability, and, most importantly, a product that would represent enough of a payoff to justify both the risk and cost of scale-up of this new class of material.

Initial scale-up efforts have focused on low-pressure turbine blade (LPTB) applications in larger jet engines. As the engine gets bigger, the turbine blades become larger, causing both the disk and shaft to become heavier. Replacement of the conventional nickel-based turbine blades with gamma blades eliminates this cascading engine weight-increase problem. Gamma alloys are half the density of nickel alloys, but have a higher modulus at operating temperature. These properties, combined with adequate creep resistance, make gamma attractive for several stages of the LPTB.

The first cast-gamma LPTBs to successfully run in an engine were Ti-48-2-2, cast at Howmet's TiCast Division in Whitehall, Michigan. These were cast 2.5 mm per side oversize in order to manage solidification porosity and achieve fill of the mold. Ninety-eight machined-to-size blades were assembled into a CF6-80C test engine and tested through 1,000 engine cycles without mishap. An additional 500+ cycles were run with seven blades of another gamma alloy inserted into the set, again without mishap. With the successful completion of more than 1,500 engine cycles, the implementation program for cast Ti-48-2-2 LPTBs was initiated. In parallel with the LPTB development work at General Electric Aircraft Engines (GEAE), cast Ti-48-2-2 has been selected as the alloy to be used for the NASA High-Speed Civil Transport (HSCT) and Engine Propulsion Materials programs.

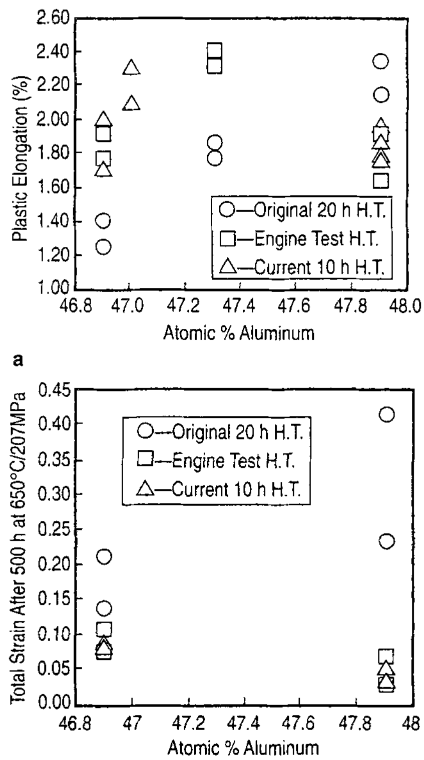


Figure 2. (a) Room temperature ductility versus aluminum content and (b) creep response versus aluminum for three different heat treatments.

Table I. First-Tier Design Properties of Cast TiAl Alloys and Cast Superalloys at 25°C

	Cast Gamma Alloys	Cast Nickel-Based Superalloys
Density (g/cm^3)	3.9	8.3
Yield Strength (MPa)	275–380	850
Ultimate Tensile Strength (MPa)	360–500	1,000
Ductility (%)	1–3	3–5
Modulus of Elasticity (GPa)	160–175	206
Poisson's Ratio	0.27	0.29
Cofficient of Thermal Expansion (10^{-6}/°C)	10.8	14.8
Thermal Conductivity (W/m · K)	22	11
Maximum Use Temperature (°C)	800	1,000

Table II. Specific Properties of Gamma Alloys and Superalloys Normalized with Respect to Density

	Cast Gamma Alloys	Cast Nickel-Based Superalloys
Yield Strength (MPa/g · cm^{-3})	70–100	102
Ultimate Tensile Strength (MPa/g · cm^{-3})	90–130	120
Modulus of Elasticity (GPa/g · cm^{-3})	41–45	25

EFFECT OF COMPOSITION AND MICROSTRUCTURE

Currently, it is nearly impossible to separate the topics of composition and microstructure for Ti-48-2-2. Aluminum is the most influential element in the gamma TiAl alloy system, since it basically controls (with the aid of heat treatment) the ratio of gamma to alpha-two in the alloy. The morphology of the alpha-two (lath, blocky, or globular) is controlled by heat treatment. The variation of aluminum permitted in Ti-48-2-2 is about 2 at.%, which, with the current heat treatment, produces consistent ductility and creep resistance with tolerable variation in yield strength and toughness (Figure 2).

a 50 μm

b 50 μm

Figure 3. (a) A cast structure with 47.9 at.% aluminum and (b) 46.6 at.% aluminum.

The two structures shown in Figure 3 represent the structure variation produced by the current heat treatment over the aluminum range specified for Ti-48-2-2. The structure in Figure 3a (47.9 at.% aluminum) is primarily equiaxed gamma while Figure 3b (46.6 at.% aluminum) is primarily lamellar, however, both produce useful fracture toughness—Kq = 25.8 Mnm^{-3} and Kq = 28.7 Mnm^{-3}, respectively.[2]

DESIGN PROPERTIES

Generally, designers use two different tiers of materials properties when designing components for a new application. First-tier structural design properties are used to choose a material for a specific application. Properties such as strength, stiffness, maximum-use temperature, and ductility are evaluated for several classes of materials with respect to the component's design parameters. Second-tier design properties such as fatigue, crack growth, creep, and creep-fatigue interaction are used to finalize the design and assess the service life of the actual component. Typically, there is a large amount of first-tier design properties for newer classes of materials. Second-tier design properties usually take years to be fully characterized. This is true for the gamma alloys.

Cast gamma alloys are currently being used or considered for jet-engine components as a substitute for nickel-based superalloys because of their superior specific properties. Like all advanced materials, cast gamma has its advantages and disadvantages. In general, designers should take into account cast gamma's lower ductility, toughness, and fatigue resistance when considering it for an application. In designing component-attachment points and interfaces, careful consideration should be placed on the thermal expansion characteristics of gamma alloys as compared to other materials. In some cases, due to its relatively low thermal expansion, a gamma-to-superalloy joint could produce a significantly higher thermal stress in the gamma component, causing a premature failure.

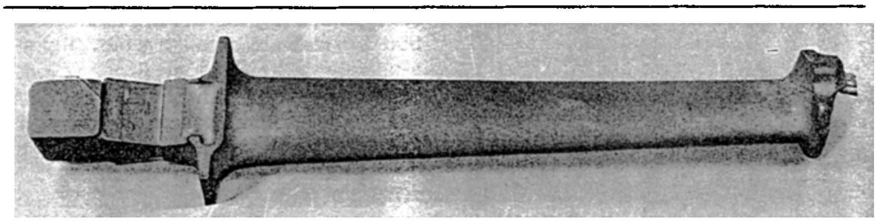
First-Tier Design Properties

First-tier design properties at room temperature for gamma alloys and cast nickel-based superalloys are compared in Table I. Gamma alloys have a distinct advantage when comparing density, coefficient of thermal expansion (CTE), and thermal conductivity. All of these properties are important in the design of advanced jet-engine components. Density is important to achieve lightweight components. A gamma alloy's lower CTE can minimize thermal fatigue problems, and its higher thermal conductivity can increase its use temperature by means of external cooling.

If strength, ductility, and stiffness properties are normalized with respect to their respective densities, then gamma alloys start to have a distinct advantage over conventional superalloys (Table II). Specific yield strength and specific ultimate tensile strength of gamma alloys are similar to those of superalloys. Gamma alloys have specific moduli that are more than 50 percent higher than superalloys, making them more attractive for deflection-limited components.

Second-Tier Design Properties

The average 1,000 hour rupture strength at 705°C for cast superalloys is approximately 365 MPa. By comparison, the average 1,000 hour rupture



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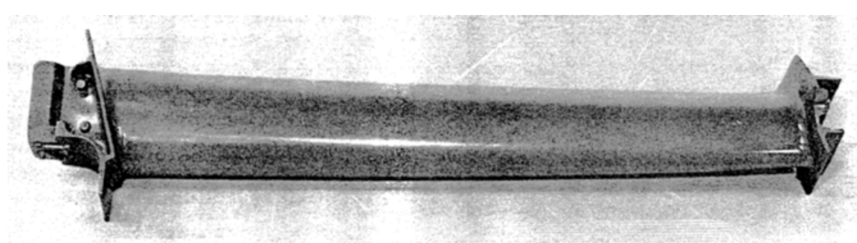


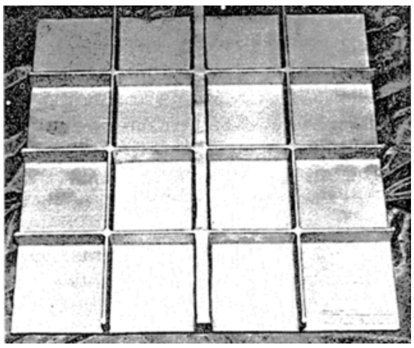
b

Figure 4. (a) A crude-shape CFC-80C LPTB cast-gamma blade and (b) a GE90 cast-to-size gamma LPTB.

strength of cast gamma alloys is 275 MPa, a significant disadvantage. However, gamma alloys at less than half the density of a superalloy will have a significant advantage over a superalloy when compared on a specific creep resistance basis. Normalizing these rupture strengths with respect to their respective densities, cast gamma will have a specific rupture strength of 70 MPa/g · cm^{-3} compared to cast superalloys with 45 MPa/g · cm^{-3}. Thus, for jet-engine components that require a high degree of creep resistance at a minimal weight, a gamma alloy is a good candidate for the application.

The fatigue behavior of cast gamma alloys exhibits large amounts of scatter in life,[3,4] which is due to the flatness of the fatigue curve and the fact that the aluminum content plays a major role in the variability in microstructure and, consequently, in fatigue lives.[3] It has been observed that different volume fractions of the γ phase influences low-cycle fatigue (LCF) lives. An increase in the volume fraction of γ phase will decrease the cast gamma's fatigue resistance. Crack-initiation sites are typically located at casting defects and γ grains. It has been shown that the size and distribution of these defects and γ grains correlate well with the observed scatter in fatigue life.

Recent fatigue investigations that include fatigue crack growth (FCG) observations have shown that more than nine percent of life is spent in crack initiation for cast gamma alloys.[3] This conclusion is supported by examinations of surface replications of interrupted test specimens, post-mortem examination of specimen fracture surfaces, and the observation of relatively steep Parrish region slopes in cast-gamma FCG data.[3,4] Results from these observations indicate that a relatively small fraction of the total fatigue life is crack propagation. Further, a comparison of cast-gamma FCG data to other cast metals shows a faster FCG rate for gamma.



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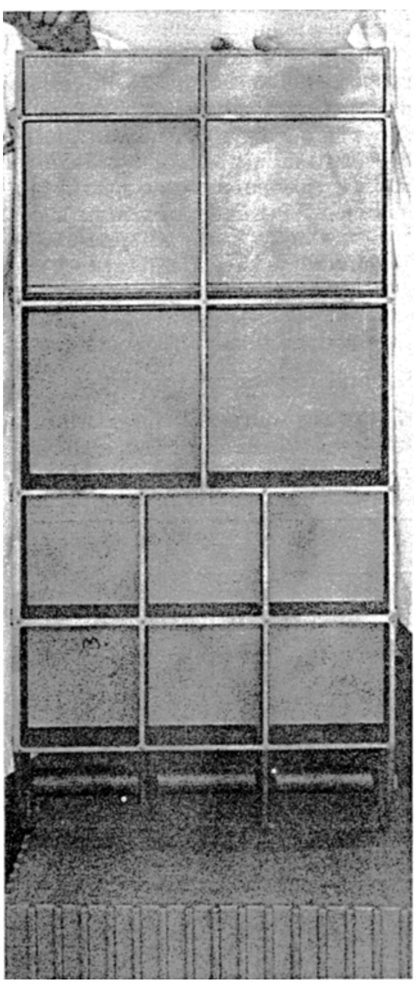

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Figure 5. (a) A cast 30.5 cm × 30.5 cm rib-stiffened face plate and (b) a cast-gamma prototype flap section of the HSCT.

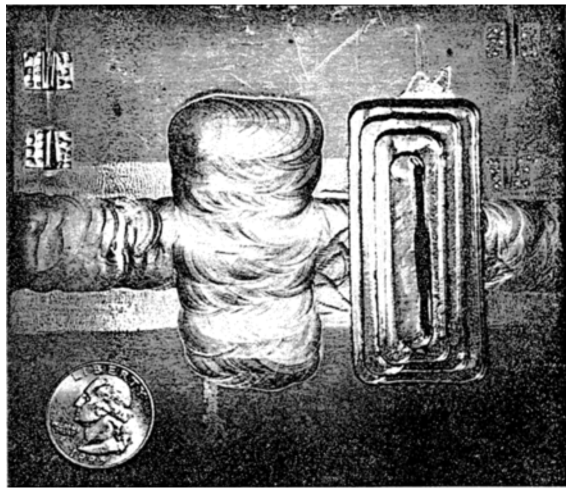

Figure 6. A gas-tungsten arc welding repair.

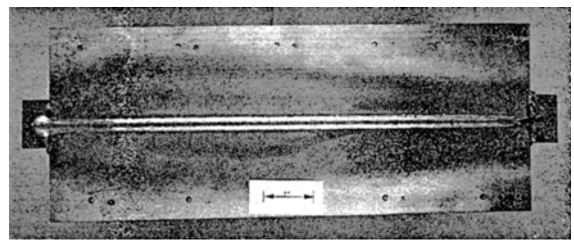

Figure 7. A defect-free EB weldment of cast Ti-48-2-2.

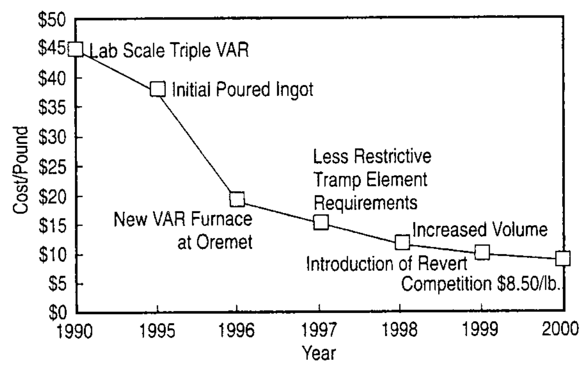

Figure 8. The cost per pound of cast Ti-48-2-2 ingot.

CASTING ACHIEVEMENTS

Process development to support production volumes of castings of TiAl has initially presented some unique challenges. The low ductility of gamma alloys presents more of a problem during manufacturing than in service. As a result, much effort to develop casting techniques that deal with the ductility issue has occurred. In addition to basic process development, process capability issues were addressed, including cost, quality, and the ability to manufacture a near-net-shape component as opposed to an oversized bulk shape, thereby, enhancing its value for the potential customer.

Investment-casting technology for Ti-48-2-2 has progressed from making crude shapes to the net-shape cast GE90 LPTB (Figure 4). Figure 4a is considered a crude shape because it was simply a matter of filling a mold with metal; no dimensional or x-ray requirements were placed on the casting. When castings were eventually manufactured for engine testing, they had to be produced with a great deal of overstock (2.5 mm) per side in order to assure a sound final product that would meet drawing requirements. In order to appreciate the dramatic advancement in gamma-casting technology, compare Figure 4a, cast by Howmet in 1992, to Figure 4b, cast by Precision Castparts Corporation in 1996. Currently, net-shape investment castings as large as LPTBs are produced in Ti-48-2-

(Continued on page 76.)

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September 20–23, 1998, Tokyo. The beginning of the 21st century will likely be characterized by economical and environmental issues favoring further cost reductions and the preservation of the global environment. Zinc-coated steel is one of the materials to meet these requirements. This conference will discuss ways to reduce the production cost of zinc-coated steel without impairing its environmental friendliness and prolonged lifetime. **Abstracts due December 15, 1997, to** C. Onozuka, JATIS, Sogo-Kojimachi No. 3 Bldg., Kojimachi 1-6, Chiyoda-ku Tokyo 102, Japan; telephone (81) 3-3239-4565; fax (81) 3-3239-4714; e-mail KYD00356@niftyserve.or.jp.

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Titanium *(Continued from page 50.)*

2. The next step is to make near-net-shape large structural casting sections and to fabricate them into much larger finished structures by a combination of welding and machining.

Although several components have been cast from a wide range of gamma compositions worldwide, no gamma casting has been attempted in the size range envisioned for the nozzle section of the HSCT. From the conceptional design it was clear that no hot-isostatically press (HIP) vessels existed that could HIP a complete rear divergent flap. The HIP vessel, shell-making, and casting-furnace size limitations dictate that the HSCT nozzle divergent flap be cast as segments and joined during the final stages of assembly. To facilitate the development of the various sections, a variety of subelement casting configurations were produced, ranging in size and complexity from the simple rib-stiffened face plate casting, to the larger, more complex I-beam, and culminating in the very large, simulated flap section (Figure 5). The flap section shown in Figure 5b is believed to represent the biggest gamma TiAl casting yet produced. Nine discrete castings (of about this size) will be used to assemble one of the HSCT divergent flaps.

WELDING

Cast Ti-48-2-2 has been shown to be weldable by gas-tungsten arc welding (GTAW) for in-process enhancements in the foundry and for structural fabrication by electron beam (EB) welding. Simple castings of Ti-48-2-2 have been successfully repair welded. More complex geometry parts like the rib-stiffened face plate and sections from the prototype flap have also been repaired. These repairs are done in an inert atmosphere while the part is held at a uniform, elevated weld temperature. A relatively complex combination of simulated repair welds using GTAW on a 12.7 mm thick plate is shown in Figure 6.

Successful EB weldments of cast Ti-48-2-2 up to 254 mm in length and 12.7 mm thick are shown in Figure 7. This type of weldment requires some special handling, but has been produced on a regular basis without difficulty. When properly heat-treated, the all-weld metal's tensile properties at room temperature are generally better than those of the base metal, while the creep and fracture toughness are equivalent.

COST REDUCTION

The implementation of cast Ti-48-2-2 would not be a very long story if it were not for the cost reductions that have been accomplished, even while the technology was being developed. Normally, cost reductions wait until after implementation of a new system, but in today's economy, it is unthinkable to propose a material for implementation that will cost the customer more than that already in service.

For Ti-48-2-2, cost reductions have occurred at every step of the processing of the alloy. The initial idea of investment casting to near-net shape is a cost reduction from forging or extruding followed by machining to final dimensions. However, as the precursor to investment casting, the cost of the alloy itself must be considered, and that has been steadily reduced from $45 a pound down to currently $20 a pound; it is expected to reach $8.50 a pound shortly after full production is implemented (Figure 8).

Heat treatment is another component of cost, and initially many gamma alloys required very long and expensive heat treatments to attain useful mechanical properties. Further, the range of aluminum content over which the individual heat treatments actually produced repeatable properties was also limited. Initially, Ti-48-2-2 was heat-treated for 20 hours at 1,300°C in vacuum to attain useful ductility, but the creep behavior and room temperature ductility varied too much over a very narrow aluminum range, as shown in Figure 2. In order to smooth out the creep performance over a reasonable aluminum range, a 70 hour heat treatment, not including the HIP cycle, was invented. This cycle was not usually long, but was very expensive. Currently, the Ti-48-2-2 heat treatment is ten hours, including the HIP cycle, and has produced constant ductility and creep behavior over the specification range of aluminum.

The flattening out of the ductility and creep behavior over a wider range of aluminum with the ten-hour thermal cycle reduces cost in two ways. First, the heat treatment is less expensive. But more importantly, the working aluminum range is larger, which allows the alloy producer to lower costs due to a diminished risk of producing scrap heat due to missing the aluminum composition window.

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