Gamma Titanium Aluminides: Their Status and Future

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Gamma alloys, based on the gamma titanium aluminide (γ-TiAl) intermetallic compound, are emerging as a revolutionary engineering material for high-temperature structural applications. This article discusses the historical background as well as the status and future prospects of gamma alloy technology in the areas of alloy development/design, process development, and applications.

INTRODUCTION

The first measurements of mechanical properties and oxidation resistance in a binary TiAl cast alloy were made in the early 1950s. Since then, several reports have confirmed various properties beneficial to high-temperature structural applications, including low density, excellent high-temperature strength retention, high stiffness (especially at high temperatures), thermal expansion comparable to current alloys, good oxidation resistance, and hot corrosion resistance comparable to, or better than, those of current alloys.[1–15]

The first major gamma alloy development program was initiated by the U.S. Air Force Materials Laboratory and was conducted by Pratt and Whitney in East Hartford, Connecticut, from 1975–1983. This exploratory program evaluated numerous alloy compositions through wrought processing and recommended Ti-48Al-1V-(0.1C) as the best alloy composition on the basis of ductility and creep resistance.[1,2] Nevertheless, its properties in the fine duplex microstructure condition were not adequate for the requirements of any engine components. At the end of the program, alloy castings were also evaluated; however, the properties were found to be unsatisfactory as the large-grained-cast lamellar microstructures resulted in poor ductility and low strength.

A few years later, the second major development program, initiated again by the Air Force, was performed by General Electric at Schenectady, New York, from 1986–1991. Largely based on the knowledge accumulated during the first program effort and other independent investigations, the effort identified Ti-48Al-2(Cr or Mn)-2Nb as the best second-generation alloy composition.[6–10] The alloy, produced through rapid-solidification wrought processing, had a fine duplex microstructure and exhibited improved ductility, strength, and oxidation resistance over the first-generation gamma alloys. Knowledge of the effects of alloying elements, as well as the composition of the properties, progressed for both binary compositions and multicomponent alloy systems.

As with most metallic materials, investment casting was used as the first process route for producing experimental gamma components.[6–10,12,14] Since Howmet initiated a major investigation late in the 1980s, several companies worldwide have tried to develop investment casting technology for second-generation gamma alloys. The gamma casting technology has advanced considerably after solving various problems such as cracking, hot tearing, surface-connected porosity, filling, and dimensional accuracy. In addition, much effort now appears to be directed toward establishing low-cost, consistent manufacturing processes that incorporate alloy composition and its variations, materials properties, casting conditions and parameters, fillability, hot isostatic pressing (HIPing), and final microstructures of interest.[14]

However, as-cast, Ti-48Al-2Cr-2Nb is unacceptably low in ductility and strength for many applications, due mainly to the coarse and nonuniform cast lamellar microstructure that is not readily removed by HIPing. Empirical efforts have been made to control the lamellar structure through annealing treatments, making finer mixtures of gamma grains and residual lamellar regions called casting duplex microstructures of about 100–200 μm grain size. The casting duplex from Ti-47Al-2Cr-2Nb exhibits a reasonable balance of properties (though at relatively low levels), and has recently been demonstrated as a viable engineering material through rigorous engine tests.

Investigations to refine cast microstructures have been made, resulting in the development of cast XD alloys first at Howmet in 1990. Two XD alloys, Ti-(45, 47)Al-2Mn-2Nb-0.8 vol.%TiB2, have been tested worldwide and appear to be establishing themselves as engineering alloys. The inoculation ability of boron in cast alloys was used in Japan and Germany to develop the cast alloys Ti-47Al-1.6Fe-1.4V-1.4B and Ti-47Al-3.5(Nb, Cr, Mn)-0.8(B, Si), respectively.[2–5]

Databases for the second-generation cast alloys are being established through extensive property evaluation on a few fixed processing-microstructure conditions. Most of the properties measured at temperatures up to 760°C appear to be comparable to, or better than, those of the counterpart nickel-based superalloys that they are to be substituted for when the properties are adjusted for density.[3,14] These properties include stiffness, high-temperature strength, creep, oxidation resistance, and corrosion resistance. Fatigue crack growth, impact resistance, and ductility are of concern, and appropriate measures may be needed in design strategy to accommodate such deficiencies.

CAST GAMMA ALLOYS

Various gamma components for turbine engines have been identified for rotational parts such as low-pressure turbines (LPTs), high-pressure compressor blades, and high-pressure turbine blade cover plates, and stationary parts such as transition duct beams, vanes, swirlers, various cases, and nozzle flaps and tiles.

For the past few years, the databases and damage tolerances of various gamma alloys have been assessed for some of the identified components through various qualification tests (e.g., bench tests, rig tests, and engine tests) by several companies, including General Electric, Pratt & Whitney, MTU, Rolls-Royce, and IHI. Perhaps the most significant qualification test was the rigorous engine tests conducted in 1993 and 1994 by General Electric on a full-set wheel of 98 LPT-cast gamma blades made of Ti-47Al-2Cr-2Nb. The two successful engine tests included more than 1,500 simulated flight cycles. The test was a milestone for gamma and created a definite, though not totally certain, confidence in the material within the gamma TiAl community and with designers.

Through these and other tests, the cast gamma alloys are proving to be technologically sound materials and, with some design modifications pertinent to each component, can replace nickel-based superalloys in use for selected engine components. Accelerated uses of gamma alloys in replacing the current materials will be warranted when many uncertainties about the performance in the field are answered and low-cost manufacturing processes are demonstrated for important types of components.[3,14,15]

Cast TiAl alloys are also intended for use in automotive engine parts such as turbochargers and valves. Recent engine tests show that a cast TiAl turbocharger rotor exhibits better acceleration response and higher maximum rotational speed than its counterpart, the Inconel rotor. However, there are some drawbacks to using a TiAl turbocharger, such as low ductility at room temperature, a concern of high-temperature oxidation resistance, and relatively high production cost. Exhaust engine valves appear to be an ideal application for gamma alloys and are expected to replace the current valves made of steel and/or nickel-based alloys. The properties of gamma alloys in any microstructural forms well exceed most of the property requirements, as was demonstrated through a series of extensive qualification engine tests conducted at General Motors recently. The remaining barrier appears to be the development of a low-cost, high-volume manufacturing method. At present, casting and perhaps reactive sintering are the two most important production methods, and intensive production and alloy modification efforts to reduce the cost are underway worldwide.[3,14,15]

FUNDAMENTAL ADVANCES

While casting gamma technology has been progressing in producing components, the advances in the understanding of the fundamental aspects of the alloys have been equally impressive. The midsection of a Ti-Al binary phase diagram has been established, and some ternary diagram work has progressed. The sequence of phase transformations involving α decomposition is qualitatively understood.

For the Ti-(45-48)Al based alloys, decomposition takes place in several paths (depending on cooling rate and method), yielding lamellar structures under relatively slow-cooling "feathery"-type structures when air cooled and massive gamma when water quenched. Investigations have concentrated on lamellar structures for formation mechanisms, growth kinetics, and alloy designs. Extensive investigations of the deformation behavior of unidirectional lamellar material has been conducted mainly at Kyoto and Osaka universities to establish the deformation anisotropy. Fine details and various mechanical behaviors are under continuous investigation worldwide. Advanced understanding of the lamellar structure will be crucial for designing optimal lamellar-based microstructures.[4–9,12–14]

Based on knowledge of the phase relations and transformations, progress has been made in the controlling and understanding of microstructures developed in wrought-processed alloys at Wright-Patterson Laboratory as well as other institutes. Four different types of standard microstructures were identified: near-gamma, duplex, nearly lamellar (NL), and fully lamellar (FL). The first two are fine-gamma-grain based (less than 70 μm), the last two are lamellar-based, and FL material, in general, is large-grained (greater than 350 μm). Gamma alloys show the so-called ductility-toughness inverse relation at temperatures below the brittle-ductile transition temperatures. Fine grain microstructures yield improved tensile properties but low fracture toughness; the reverse is true for large-grain FL material. This relation is explained by correlating grain size, pileup-dislocation-density, and the deformation anisotropy of the lamellar structure. However, a critical grain size appears to be responsible for the abnormally high-strength gain with decreasing lamellar spacing. Creep resistance is higher for FL than duplex microstructures and appears to increase with grain size. Additions such as Si, C, N, Ta, and W appear to improve the creep resistance, although each mechanism is known only qualitatively. High-cycle fatigue resistance is excellent (at least up to 800°C), but becomes oxidation limited, in general, at higher temperatures. Relatively low-fracture toughness and very fast fatigue-crack growth rates are of concern because the material's life will then be limited in the presence of relatively small existing or created defects or flaws. Nevertheless, both properties are improved in FL material and with increasing grain size.[3–5,12,14,15]

WROUGHT ALLOYS

It is estimated that, considering the inverse ductility-toughness relationship and the beneficial effects of lamellar structures on fracture toughness, creep, high-temperature fatigue properties, and fatigue crack growth resistance, FL material having roughly a 100–400 μm grain size should show an improved balance in properties. The exact magnitude should be a function of property requirements, component configurations and dimensions (thickness), and processing methods.

Since such a controlled FL grain size is difficult to produce in Ti-48Al-2Cr-2Nb, and because alloys containing large amounts of boron (such as XD alloys) are not suitable as wrought alloys, extensive investigations have been conducted to design refined lamellar structures in wrought alloys. Such designed materials have been obtained in relatively thin sections through various techniques, including by adding small amounts (0.1–0.3 at.%) of boron (yielding thermomechanical-treated [TMT] lamellar), through appropriate high-temperature extrusion (producing thermomechanical-processed [TMP] lamellar), or by appropriate alloy modifications that widen or lower the high-temperature ($\alpha + \beta$) phase field (resulting in refined FL). Methods to control lamellar spacing were also developed utilizing the lamellar formation mechanism and growth kinetics. Fundamentally, we are just beginning to sufficiently understand the essential aspects of designing lamellar structures.[3,4,14]

Almost at the same time, investigations on workability and texture development during hot working have been extensively investigated in the United States, Japan, and Germany. By using concurrently developed process modeling, advances in process development have been realized for wrought processing in areas such as primary processing, secondary processing, and component forming. Ingot conversion through isothermal forging, extrusion, and multistep processing has been commonly practiced with and without homogenization treatments on a small scale. Conversion of large ingots (more than 250 kg) is now possible through multistep processing, although more details have to be identified before production scale practices can be implemented. Ingot breakdown by nonisothermal forging has been shown to be feasible using a canned workpiece. Pack-rolling technology has been advanced, using forged plates and prealloyed powder compacts, with sound sheet of 800 mm × 300 mm × 1.5 mm currently produced. The availability of the size and microstructural homogeneity of starting plates appears to limit production of larger sheet. In general, hot-worked gamma material is highly formable, isothermally, at temperatures as low as 1,000°C. Prototype blades having twisted air foils have been successfully forged in this manner, and rolled sheet has been superplastically formed into various complex-shape parts.

Forming by hot-die forging and high-rate extrusion, however, is a hurdle to overcome if wrought gamma components are to be produced cost-effectively. Recent trials of automotive valve extrusion in current production facilities, though limited to canned or insulated material, indicate that such high-rate forming of gamma may eventually be feasible if optimum processing conditions and parameters are identified on preconditioned material.[6–10,14,15]

The production of gamma ingots has been practiced using various melting and casting methods, including induction skull melting, vacuum arc remelting (VAR), plasma arc melting (PAM), and vacuum induction melting. Ingots having a 30 cm diameter are routinely produced by the VAR technique. Ingots having a 36 cm diameter and weighing more than 250 kg have been produced using VAR and PAM techniques, and production of larger ingots by PAM appears to be feasible.

The main concerns in scaling-up are cracking, control of chemistry (especially the aluminum level), and compositional variations along the ingot length. In addition, methods to produce ingots with more refined and uniform cast structures are yet to be developed.[15]

ALLOY MODIFICATION

As the importance and necessity of the properties pertinent to specific components are recognized, increasing efforts have been made to develop specific materials through microstructure control and alloy modification. The thrust of this effort (aimed primarily at wrought alloys) was to develop lamellar-based structures that are fine enough for specific component thicknesses and coarse enough to retain the most desirable properties. The important microstructures developed from the effort include refined-fully lamellar, TMT, and TMP microstructures. The most dramatic improvements were observed in TMP materials, with strength levels reaching as high as 1,000 MPa at reference temperature and more than 500 MPa at 1,000°C.

Nevertheless, considerably more work has to be done in various aspects such as understanding the formation mechanisms, thermal and mechanical stability, process control (including heat treatment cycles), databases, property evaluation, and characterization of damage tolerance. It will also be important to raise the property levels (creep and strength) by adding small amounts of Si, C, N, or O, without affecting other properties. With the above modifications, the component-specific gamma materials are expected to exhibit improved balances of properties and/or increased use temperatures by 50–100°C. These types of improvements appear to be possible in cast alloys by alloy modifications and by refining coarse-cast lamellar grains into fine lamellar grains through novel heat treatment cycles.[3,4,14]

Further increases in the use-temperature of gamma material to above 850°C could be very profitable in the future and may be accomplished through the development of novel processes, new alloys, and effective surface treatments (including protection) methods. The novel processing methods, which are under exploration, are aimed at producing material having aligned lamellar structures by directional solidification of columnar grains and/or directional extrusion of lamellar grains. These methods, however, have yet to show their engineering feasibility to produce the intended microstructures; then, the resulting microstructures or materials must demonstrate their expected higher temperature capabilities as well as damage tolerance comparable to those of current gamma alloys.

Increases in both oxidation resistance and higher temperature strength levels may require drastic departures in composition from the current gamma alloys. One example can be alloys containing large amounts of niobium. Development of such new alloys requires prolonged, worthwhile research efforts. In the end, however, it appears inevitable that surface protection of any gamma alloys must be developed if they are to be used at temperatures above 800–850°C. Several preliminary or developmental efforts in this area suggest that this is challenging and will not happen quickly.[14]

CONCLUSIONS

In summary, gamma alloys are emerging as important engineering materials. The current alloys, basically cast alloys developed under collaborations, meet property requirements of selected turbine, as well as automotive, engine components. With the development of appropriate design methodologies and cost-effective manufacturing methods, these alloys are certain to be implemented for selected applications soon.

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