Investment Cast Titanium for Aeroengine and Aircraft Structural Applications

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ABSTRACT

Investment cast titanium alloys are increasingly being recognized as affordable solutions that are capable of meeting the stringent requirements for structural airframe components. A number of innovative technology advancements have been made in the casting industry over the past five years to promote increased acceptance of castings in fracture critical airframe structures. These process improvements have resulted in higher quality castings, along with a better fundamental understanding of the static and dynamic mechanical properties associated with investment cast titanium. The U.S. government has fostered many of these improvements in order to reduce the cost of military aircraft. The following is an overview of the status of the titanium casting industry, along with a discussion of the more recent technology innovations that have made cast titanium products more attractive.

INTRODUCTION

Titanium and its alloys have long been attractive for advanced aerospace structural applications due to their high strength-to-weight ratio and excellent combination of ductility, fracture toughness and modulus. However, despite these attractive characteristics, the application of titanium and its alloys to large, highly loaded structures has been hindered due to problems associated with fabricating titanium into large structural shapes. Forging has long been the preferred fabrication method because it yields excellent mechanical properties, but limitations in size and complexity have prevented designers from achieving the design flexibility desired for complex structures. The ability to use various casting technologies to make complex structural shapes is attractive to airframe designers because casting provides both structural complexity and near-net-shape capability. Moreover, the typical lead times for titanium castings (from casting to shipping) tend to be much shorter than for forgings.

Concerns have persisted regarding the ability of castings to provide adequate mechanical properties in highly loaded critical structures. These concerns are in part related to the lack of static and dynamic databases for investment cast titanium. To compensate for this lack of confidence, designers typically apply a safety margin, or casting factor, to the strength of the cast materials under consideration. The application of a casting factor limiting the load-carrying capability of such structures has led to reluctance on the part of designers to employ castings in primary structures, mainly because the strengths tend to be less attractive due to the safety margins. Many recent efforts have been directed toward improving confidence in the design data in order to eliminate casting factors in primary-structures [(1)].

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Many quality concerns in investment castings have been alleviated through a variety of technological advances over the past 10 – 20 years. For example, vacuum arc (VAR) and induction-skull re-melting (ISR) are methods developed to melt and cast titanium alloys without contamination. Additionally, development of data regarding the reactivity of titanium alloys with a wide variety of materials has produced a number of ceramic and metallic mold materials that can be used to contain molten titanium during the casting process with a minimum amount of reaction [(2)]. The advent of hot isostatic pressing (HIP'ing) has dramatically improved the quality of titanium castings through the elimination of internal shrinkage and gas defects. Along with automated shell-processing technology utilizing robotics, these types of process improvements have substantially improved the quality of titanium castings. Moreover, these improvements have brought the titanium casting industry to a position of being able to actively compete with forged titanium products, particularly in the area of large structural castings for airframe applications. Aircraft-engine manufacturers have long employed structural titanium castings for large components, such as the fan frame shown in Figure 1.

ADVANCED TECHNOLOGIES

Computer Aided Engineering

Computer aided engineering (CAE) has had a resounding effect on almost every aspect of casting manufacture, from the initial receipt of the customer data through wax die manufacturing, measurement of dimensional characteristics of the casting and the production of rapid prototypes by various methods [(3)]. In addition, the influence of computer modeling to simulate various aspects of the casting process is revolutionizing process development in the industry. The production of castings is more frequently achieved by direct transfer of the electronic data to a tool shop for wax die fabrication, to a rapid prototyping facility for pattern fabrication or to a foundry to generate gating tooling, fixtures and inspection routings. These changes are revolutionizing the way in which engineers interface with customer requirements. With electronic data, process modeling is conducted more directly because the part geometry is immediately available in digital form. Process modeling is also used in many steps in the investment casting process, including wax injection, dewax, mold-filling, solidification and stress analysis to analyze for mold cracking. These steps require significant training to enable the process and product engineers to most effectively use these CAE tools. When used most effectively, the utilization of CAE approaches can greatly shorten the cycle time, reduce cost and provide an improved quality product to the customer.

To use CAE, the investment casting industry must standardize on the protocols employed for data transfer, tolerance definition, specifications, etc. A major driver for the adoption of computational methods in all industries is the dramatic reduction in the cost of engineering workstations used for many of the approaches described, along with vastly increased speed and capability of such equipment. Without these enhancements, the approaches currently being used for many of the analytical methods would be far too costly and time consuming. Presumably costs and computational speed of the engineering workstations will continue this trend, making these methods more and more acceptable and in fact necessary in order to be competitive in the investment casting business.

Rapid Prototyping

The application of CAE methods to rapid prototyping in the investment casting industry is very pervasive using a variety of different types of equipment available for producing 3D patterns from electronic data. The patterns are not only used for the production of castings, but they can also be used for engineering prototypes, tooling and a number of other uses. Several different approaches to the production of rapid prototype patterns have been employed at Howmet, including stereolithography patterns (SLA) and selective laser sintering (SLS), as illustrated in Figure 2. Howmet also employs a computer-aided pattern manufacturing (CAPM) method for large patterns. With this approach, methods are used to define a computer aided design description of the part to cut individual details from sheet wax. The details then are assembled into a prototype pattern. Some of these patterns can be up to 4-5 feet in length, as shown in Figure 3. Each of these rapid prototyping methods has its own advantages, but all enable the investment casting supplier to significantly shorten the lead-time to produce prototype castings without the need for expensive tooling.

Patterns produced by rapid prototyping methods have a number of important uses including early production and process development where tooling for complex components can take up to several months. For example, wax dies for large complex structures can cost between $500,000 and $1 million in some cases, and manufacturing times for these dies can take up to six months or more. With investments of this scale, designers oftentimes are reluctant to take the risk of attempting to pioneer structural castings without producing and testing prototypes. Alternately, with rapid prototype patterns, process development and process modeling can be conducted in conjunction with rapid prototyping to identify a robust process prior to the availability of a hard tool. An example of how rapid prototyping has been used successfully to significantly shorten development-cycle times is the conversion of the Bell helicopter transmission adapter for the Bell-Boeing V-22 Tiltrotor from an assembly of 44 aluminum forgings to a single cast-titanium component [(4)]. This change was both design and cost driven, but represented a certain degree of risk, since titanium-investment castings in rotorcraft primary structures had few historical precedents. To resolve these issues, Howmet and Bell-Helicopter engineers formed an integrated product team to concurrently work out the details of producing this component in cast-titanium. Rapid prototyping was used to produce prototype patterns in less than ten weeks, and the mold processing and casting parameters were developed in full detail during the next 20 weeks. With the rapid prototyping capability of the CAPM process, Bell engineers received the castings needed to refine their designs in 30 weeks instead of the usual 65.

Howmet engineers explored different gating configurations to optimize process efficiency and end product quality. As a result of this approach, the team began production of engineering and manufacturing development (EMD) parts in 48 weeks, compared to the 95 weeks it would have normally taken. Altogether, rapid prototyping and concurrent-engineering technologies helped cut the development time in half. The resulting EMD transmission adapter, shown in Figure 4, is a structurally efficient casting, which has resulted in a reduction of machining and assembly hours from more than 1,100 hours to less than 420 hours for the EMD version. A key element in this improvement is that Bell engineers gained sufficient confidence in the component quality to use a casting factor of 1.0, which eliminated property reductions and contributed substantially to design efficiency.

Process Modeling

Another technology advancement that has significantly aided in the ability to make large, complex castings, particularly where some of the more difficult-to-cast alloys are concerned, is process modeling. Recent advances, driven by the DARPA funded Investment Casting Cooperative Arrangement (ICCA) [(5)], have significantly reduced the time to construct a meshed 3D solid model (part geometry, gating, investment shell, mold wrap, and finite element mesh).

In addition to reducing model construction time, modeling accuracy has improved significantly. Process models are now able to accurately simulate the macroscopic aspects of the investment casting process, including fluid flow, heat transfer and stress. Fully coupled fluid flow and heat transfer solutions are routinely run on models as large as two million elements. Coupled thermal/stress simulations are possible on smaller models, which involve only solid state phenomena. The coupled macroscopic analysis accuracy results from the ability of the software to accurately simulate the physics of the process and identify the boundary conditions. Boundary conditions must be defined for the core, metal, shell, mold wrap, furnace environment and the interfaces between these different media, all as a function of temperature. Howmet continuously re-evaluates and refines its boundary conditions as the capability to simulate more phenomena becomes available.

The primary benefit of the process-modeling tool is minimization of porosity in castings by defining an optimal gating for the part and eliminating the trial-and-error steps that are frequently employed to develop a satisfactory gating design. These gating schemes can then be validated using molds from rapid-prototype patterns. This combination of technologies significantly reduces both the developmental-cycle times and the costs for large structural castings. An example of how this technology has been applied to a titanium casting is shown in Figure 5, which shows both the thermal distribution during solidification and the macroporosity distribution after solidification in a thin wall cast C-17 component.

Casting Technologies

Conventional sand casting cannot be used to make structurally sound titanium castings due to the extreme reactivity of molten titanium. Shell systems having limited reactivity have been developed, enabling investment castings to be used reliably. Various approaches have been used to handle the reactivity issue with titanium, including graphite shell systems, tungsten shell systems and non-reactive stable ceramic shells. The steps required to make an investment casting are shown schematically in Figure 6. Large complex titanium castings have been fabricated using these methods, as illustrated in Figure 7.

Two principle issues arise with the investment casting process. First, small pieces of shell can sometimes break off from the mold, giving rise to inclusions, which can in turn have a deleterious impact on the dynamic properties of the cast product. This has led to a number of corrective actions, such as shell processing improvements and the development of contamination control procedures (CCP) to minimize the potential for both ceramic and hard alpha defects in cast product. In order to enhance detectability of a shell indication that is cast into the component, Howmet has developed and patented a new facecoat material. This material both limits the reaction at the molten titanium/ceramic interface and increases the X-ray detectabilty of the ceramic material in the metal substrate. Additionally, titanium always reacts with the ceramic shell to some extent, giving rise to the formation of a brittle, oxygen-enriched layer at the surface of the casting. This oxygen-enriched layer is usually referred to as alpha case, since in alpha-beta alloys, the oxygen results in stabilization of a single-phase alpha structure near the surface.

One of the more innovative methods currently under study at Howmet to eliminate the potential for both alpha case and ceramic defects is the development of a gravity metal mold (GMM) casting process. The GMM process, shown schematically in Figure 8, involves the introduction of molten metal into a preheated split metallic die cavity to form a near-net-shape casting. With this process, the potential for ceramic inclusions is eliminated because the ceramic mold has been replaced with a metal mold. Another advantage of this casting process is that the cooling rate is much higher giving rise to a much finer microstructure. Moreover, the rapid cooling rate gives little time for reaction with the metal mold system, and there is little or no alpha case in GMM castings. One current limitation of the process is that only modestly sized parts, up to 35 Lb., can be formed. This is due to a limitation in the melting capacity of the GMM furnace. However, there is also an upper limit, not as yet defined, above which excessive reaction of the molten metal and metal mold will occur. While there are geometrical limitations associated with the shapes that can be produced by this method, recent development activities using a modular metal mold concept have successfully produced components of some modest complexity. However, large complex structural shapes, such as those produced by conventional investment casting, are not attainable using the gravity metal mold process. Where this technology is applicable, another benefit is that the tensile properties of GMM castings, because of their finer grain size, are excellent, as shown in Figure 9.

Inspection

A significant recent enhancement to the major CAD systems is their ability to imbed tolerances directly on the nominal geometry of a part. This ability eliminates redundant steps on the part of the designers, allows for stack-up and producibility analysis, and direct download of the files into inspection systems. For example, the toleranced models can be used to program Coordinate Measuring Machines (CMM), drive inspection routines to collect dimensional data, and conduct 3D best fit analyses of that data against the envelope created by the toleranced model.

Non-destructive inspection of large fracture critical investment cast components has posed some special problems for casting vendors in relation to detecting ceramic and hard alpha type inclusions. Conventional X-ray inspection methods have been found to be lacking in detecting these types of defects, particularly in heavy sections greater than 2 inches in thickness. More recently, phased array ultrasonic inspection methods have been explored as an alternate tool to interrogate heavier cast sections [6]. Because the process has the ability to focus the ultrasonic waves, the sensitivity is better than for conventional ultrasonic methods, and success in locating ceramic defects in sections up to 4 inches has been achieved. This is an important improvement, since for fracture critical components, it is imperative that the designers know the minimum flaw size that can be detected. Probability of detection (POD) curves are being developed by both the OEM's and casting vendors for the non-destructive inspection processes used. The designer must then base his design on the possibility that a given flaw size could occur in a critical area. Current studies are being conducted within the industry to characterize any mechanical property knockdowns associated with these flaw sizes.

MECHANICAL PROPERTIES

The tensile and HCF mechanical properties of investment-cast components typically are lower than wrought products due to the inherently coarser microstructures associated with castings. In addition, limited test data, designed to examine section size/grain size effects on the room temperature tensile properties of HIP'ed and mill annealed Ti-6Al-4V, suggest a modest decrease in tensile properties as a function of increasing prior-beta grain size. However, the data do not appear to follow a Hall-Petch relationship, which suggests that perhaps other mechanisms dominate within the grains, as the grain size becomes very large. The beta-solution plus overage (BSTOA) heat treatment has been successfully used to overcome these property losses, in part through microstructural refinement within the grains (Table 1). Titanium heat treatments are typically conducted in a vacuum furnace and use an inert-gas fan-quench to promote microstructural refinement through a martensitic transformation. Because it requires solutioning at temperatures above the beta transus, this type of heat treatment also tends to be more costly as it requires specialized process methods to maintain product dimensions. The data also suggest that tensile properties are still controlled by quench rate and section size, with larger section sizes exhibiting a reduced benefit from the BSTOA heat treatment.

Static Properties

The lack of a statistical tensile database for investment cast titanium alloys has oftentimes inhibited many designers from using investment castings for airframe primary structural applications. To overcome this shortcoming, Howmet is working closely with both PCC-Structurals in Portland, Oregon and Pacific Cast Technologies in Albany, Oregon to generate cast material for the development of statistical data for cast, HIP'ed and mill annealed Ti-6Al-4V. These efforts have been primarily funded through the Engine Supplier Based Initiative (ESBI) program sponsored by the U.S. Air Force Mantech office. The test matrix for these studies is shown in Table 2, and data are being generated for cast sections ranging from ¼ inch to 4 inches [1]. All the test material has been cast to a common specification, AMS 4985. These data will be made available for incorporation into the MIL-Handbook-5 database during CY 2001 and will assist airframe designers in implementing investment castings on advanced military and commercial aircraft. In addition to developing a database for conventional investment castings, efforts also are underway to develop a statistical database for gravity metal mold cast materials at several thickness ranges. These efforts are being funded through the Metals Affordability Initiative (MAI) sponsored by the U.S. Air Force Research Laboratory.

Dynamic Properties

The high cycle fatigue (HCF) properties of cast, HIP'ed and annealed Ti-6Al-4V are shown in Figure 10. The typical HCF runout stress for conventionally cast Ti-6Al-4V at 10^7 cycles typically falls between 60 and 70 ksi for R=0.1. This compares with a runout of ~80 ksi for mill annealed wrought product [7,8]. The use of the BSTOA heat treatment again offers the potential to improve the HCF properties through microstructural refinement, with runout stresses at 10^7 cycles typically in the range from 70 to 80 ksi [7].

Typically, fracture toughness behavior of titanium alloys is strongly dependent on the yield strength of the material, with higher yield strengths, such as those associated with wrought materials, producing lower fracture toughness values. Both mill annealed and BSTOA heat-treated cast and HIP'ed Ti-6Al-4V exhibit superior fracture toughness characteristics relative to wrought material as shown in Table 3 [8,9].

Similar to the fracture toughness, the fatigue crack growth (FCG) behavior of cast, HIP'ed and mill annealed Ti-6Al-4V show a slight advantage relative to wrought product [1], as shown in Figure 11.

SUMMARY

Due to recent technical innovations, investment cast titanium is becoming more and more capable of meeting the stringent requirements needed for fracture critical structural aircraft components. These innovations have dramatically improved the quality of cast titanium products, many of which are due to the rapid expansion of computer aided engineering technologies, rapid prototyping and solidification modeling. In the near future it is conceivable that the feasibility and design of investment cast components could be determined entirely using electronic means. For example, modeling could be used to predict static and dynamic mechanical properties based on the predicted grain size and heat treatment cooling rates at various locations in the component under consideration. In addition, the designer will be able to design the component in question based on a known detectable flaw size, and the effect of the defect on static and dynamic properties will be known. This will provide the designer maximum flexibility in determining whether a casting will meet the desired design requirements – without ever making a casting or committing to expensive tooling. These predictive capabilities are not that far away, and they will allow the designer to take full advantage of the cost saving benefits offered by titanium investment castings, even in fracture critical airframe applications.

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9. Internal Howmet Data

Table 1.Tensile Properties of Cast + HIPed Ti-6Al-4V at 70°F.

Section Size	Standard Anneal	BSTOA Quench Rate 50°F/min.	100°F/min.	150°F/min.
5/8”				
Ultimate Tensile Strength (ksi)	136	140	140	140
Yield Strength (ksi)	120	127	126	125
Elongation (%)	9.6	7.8	8.8	9.7
1 1/4”				
Ultimate Tensile Strength (ksi)	134	136	136	136
Yield Strength (ksi)	118	125	123	124
Elongation (%)	8.6	6.4	5.5	9.0

Table 2. MIL Handbook-5 Static Property Test Matrix.

Test Type	ASTM Specification	Minimum Number of Tests	Properties of Interest
Static Tests			
Tension	E-8	100	F_{tu}, F_{ty}, ε, RA, E
Compression	E-9	30	C_y
Shear	B-769	30	S_y
Bearing (E/D = 1.5)	E-238	30	B_u, B_y
Bearing (E/D = 2.0)	E-238	30	B_u, B_y

Table 3. Fracture Toughness Test Data for Cast + HIPed Ti-6Al-4V (1 1/4” in).

Fracture Toughness, K_{1c} (ksi $\sqrt{in}$)		
Mill Anneal(1)	BSTOA(1)	Wrought (typical)
120 - 150 Ke_Q	105 - 130 Ke_Q	60 - 80

(1) Short Rod

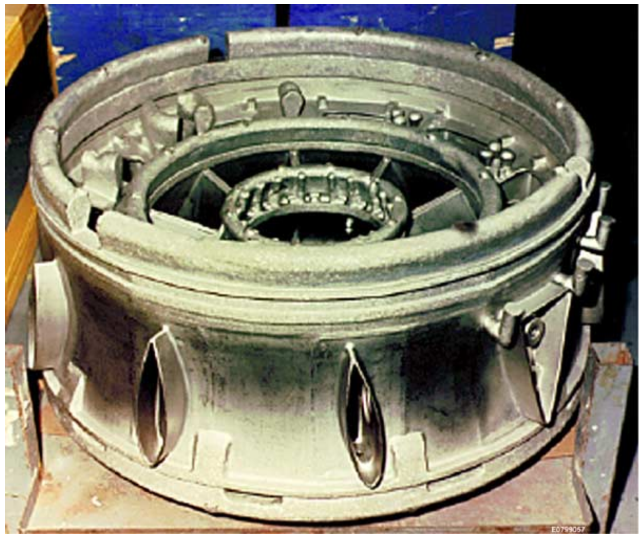
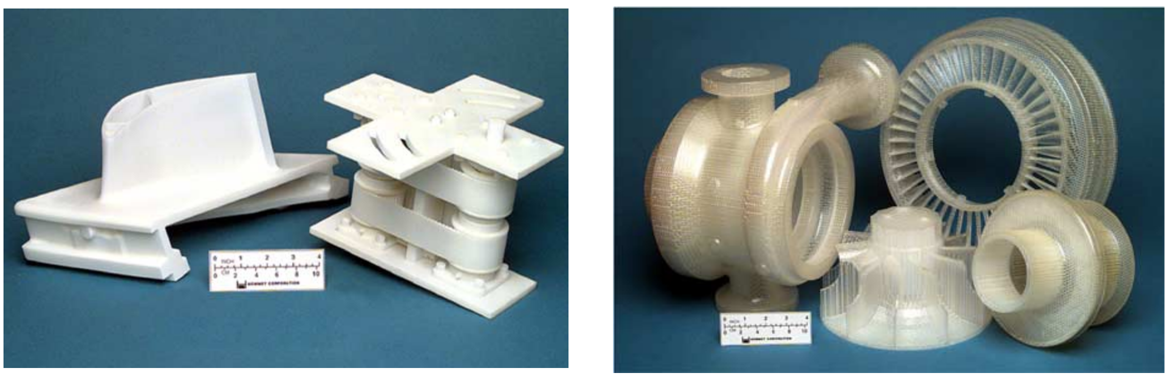


Figure 1. Investment Cast Fan Frame.



(a) (b)

Figure 2. Rapid prototype patterns made by (a) Selective Laser Sintering and (b) Stereolithography.

Figure 3. Bell Helicopter Transmission Adapter CAPM Pattern.

Figure 4. Investment Cast Bell Helicopter Transmission Adapter.

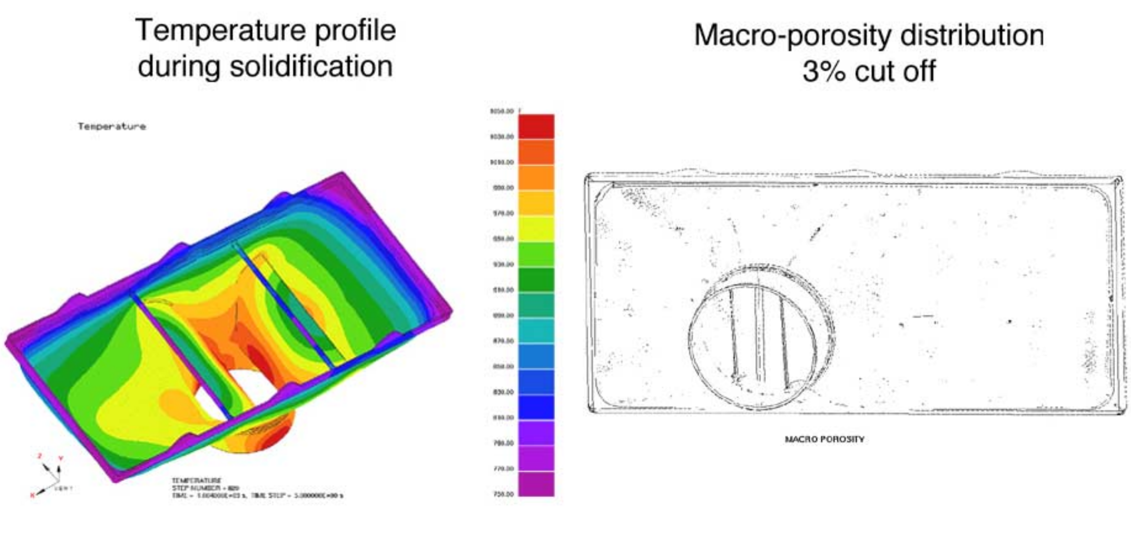


Figure 5. Solidification Model of Cast Thin Wall Ti-6Al-4V Component Showing Thermal and Macro-Porosity Distribution During Cooling.

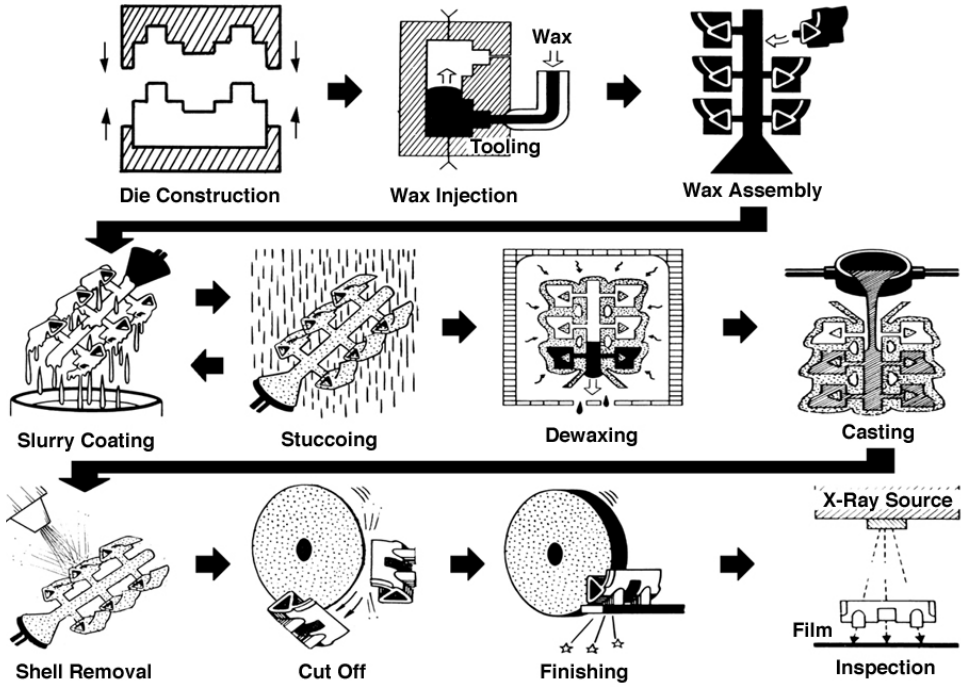


Figure 6. Schematic of the Investment Casting Process.

Figure 7. Investment Cast Side-of-Body Component.

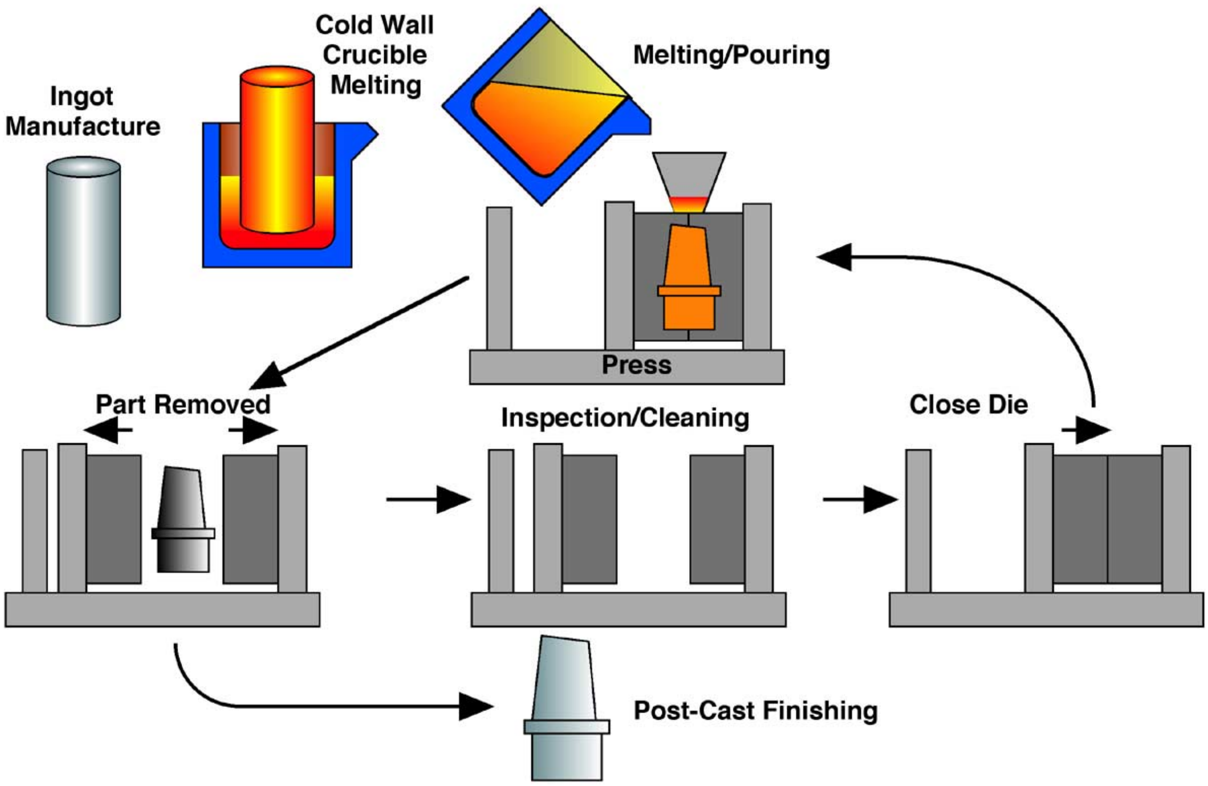


Figure 8. Typical Casting Sequence Showing Reusable Metal Mold.

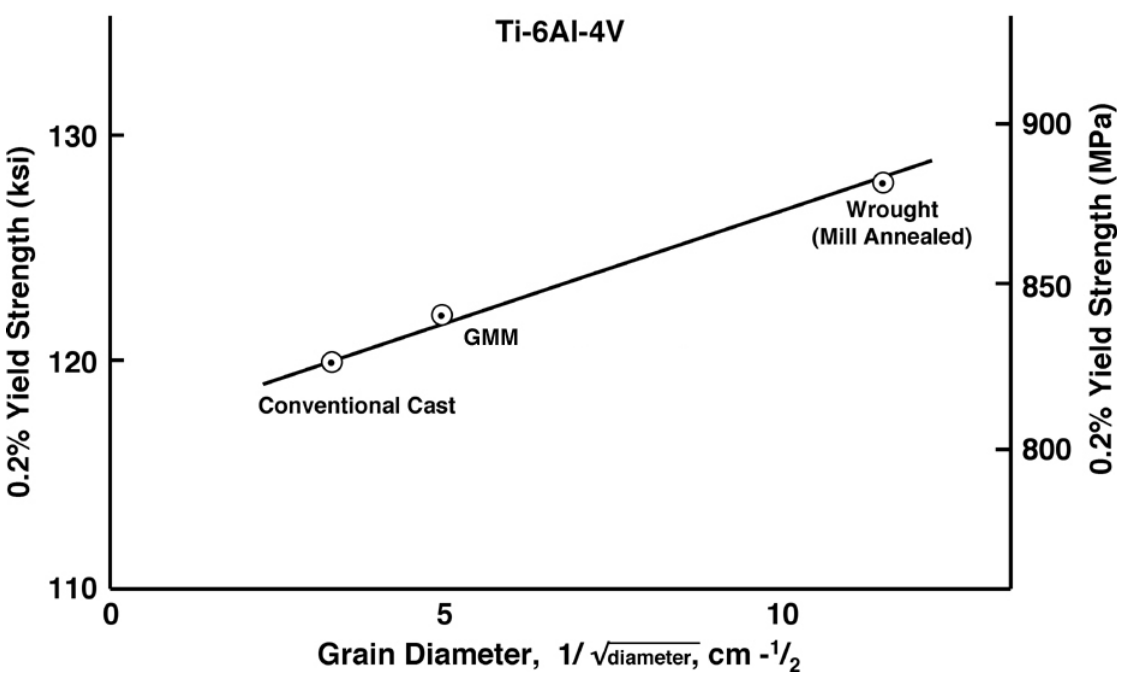


Figure 9. Effect of Prior Beta Grain Size on Tensile Yield.

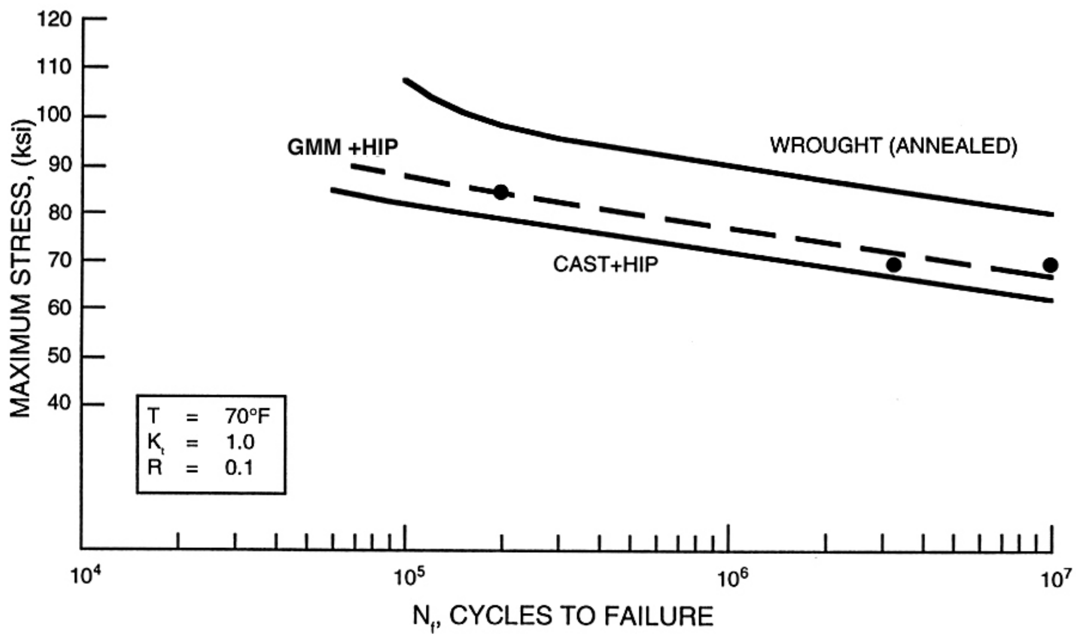


Figure 10. HCF Data for Cast, GMM and Wrought Ti-6Al-4V.

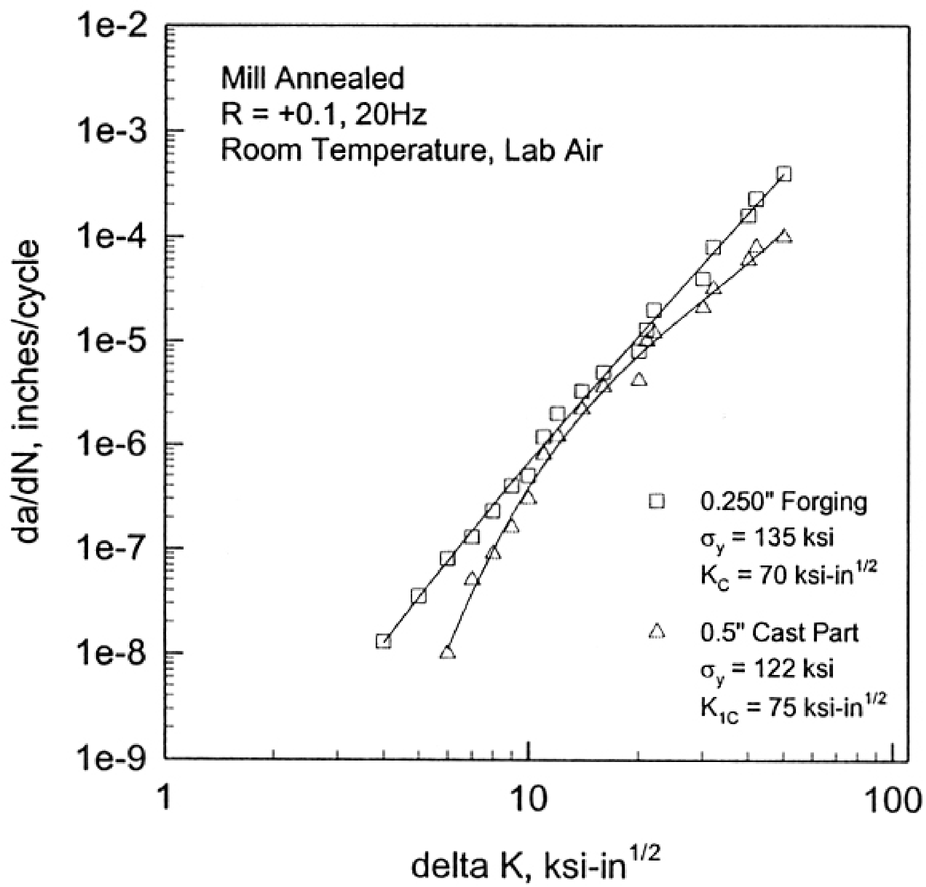


Figure 11. FCG Behavior of Cast, HIP'ed and Mill Anneal Ti-6Al-4V.

Paper # 3 by S. Veeck

Q by A. Baher – 1. “Does the HIP process just reduce the scatter in properties or does it also increase some base-line properties?” 2. Which properties benefit the most from HIPing, fatigue or static in terms of reduced scatter?”
A by S. Veeck 1. “It just reduces the scatter.” 2. “ Primarily fatigue – although static properties could be impacted, depending on shrinkage levels.”

Q by K. L. Cheung – “What material is used for the mold for die castings and is there any reaction with the mold material?”
A by S. Veeck – “6mm/VDC molds typically are steel mold materials, although high temperature inserts are selectively used. Typically solidification occurs very rapidly and the interaction with the mold is minimal.”

Q by W. Gooch – “Can the lost-form technique be used for Ti castings?”
A by S. Veeck – “We haven’t tried it, but aerospace applications precludes use due to surface finish, etc.”

Q by S. P. Godfrey – “What reject rates are achieved due to particle pick-up from shells during the lost wax process?”
A by S. Veeck – “Rejection rates are low due to the ability to remove ceramic particles from surfaces followed by welding up to repair the damaged area.”

Comment by E. Starke – “The grain size effect is most likely related to the cooling rate from above the beta transus temperature since this determines the amount and thickness of continuous alpha phase that forms along the prior beta grain boundaries which affects ductility and strength.”