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Large Structural Titanium Castings

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Large structural titanium castings have successfully replaced wrought fabrications in production gas turbine engines. As a result, new generation engines are being designed with large structural cast components. The more efficient material utilization and reduced machining requirements for large cast components compared to wrought fabrications result in lower finished part costs. As engine and airframe manufacturers exploit the cost reduction potential, the number of large structural cast components will greatly increase.

Introduction

TITANIUM is the fourth most abundant element in the Earth's crust. It occurs as stable oxides which require much energy for conversion to usable forms. The three production methods which are currently in use today are 1) magnesium reduction, 2) sodium reduction, and 3) electrolytic reduction.

Electrolytic reduction of titanium requires about 40% less energy than the other methods and producers are moving toward greater use of it.

World production of titanium metal is nearly 100,000 tons per year, with the Soviet Union, Japan, and the United States being the largest producers.

Approximately 30% of the world production is utilized in its pure or unalloyed state, typically for chemical applications.

About 50% of the world production is used to produce the 6% aluminum, 4% vanadium titanium base alloy. This high-strength-to-weight ratio alloy is the most widely used titanium alloy today. At present, the major usage is in the wrought form, but increasing amounts are being applied to castings, particularly large structural components.

The extremely low material utilization for a large structural wrought fabricated part results in much waste. Comparison of material utilization for a cast component to its wrought fabricated counterpart reveals a startling difference. It takes 20 lb of input material per pound of finished machined wrought fabricated part and 8 lb of input material per pound of finished machined cast part. In other words, 60% less input material is required to produce a casting instead of a wrought fabricated part.

Based on this discussion you can easily see that it makes good sense to utilize large structural titanium castings wherever possible. As part cost, fuel consumption, and strategic material utilization play more important roles in the aerospace industry daily, engine manufacturers are utilizing more large structural titanium castings, both as replacements for wrought fabrications in present equipment and as original design components in new generation equipment.

The areas to be discussed in the paper are current casting production; titanium investment casting techniques; design considerations; hot isostatic pressing; mechanical properties; cast vs wrought economics; and the future for titanium castings.

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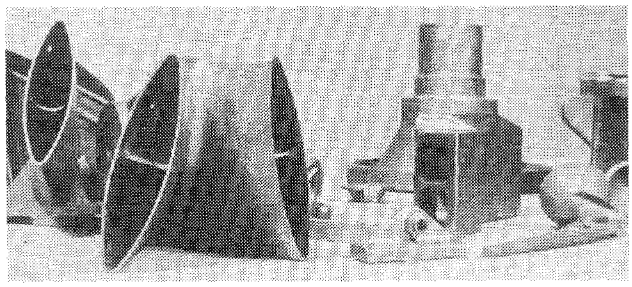

Fig. 1 Small titanium investment castings.

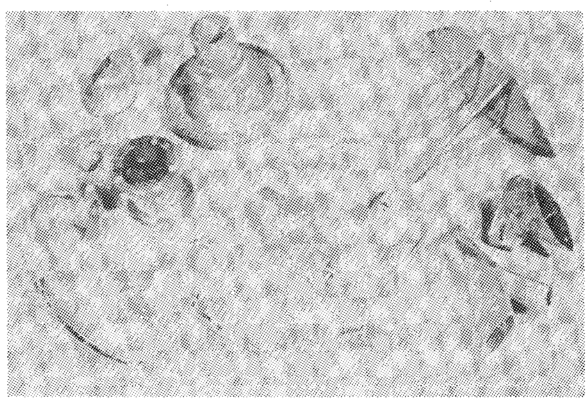

Fig. 2 Small titanium investment castings.

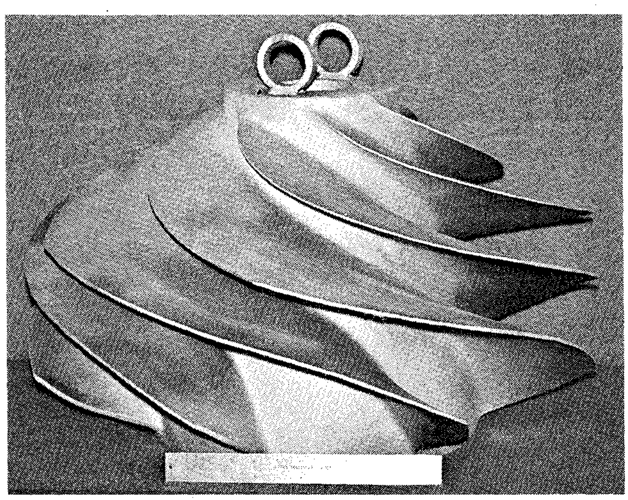

Fig. 3 Rocketdyne inducer—large titanium investment casting.

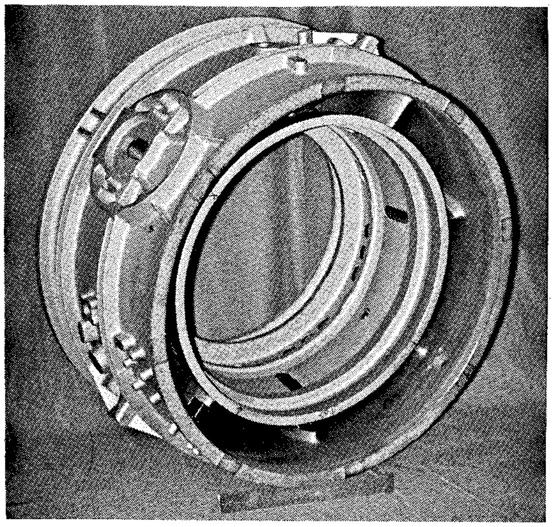

Fig. 4 MTU RB-199 intermediate case—large titanium investment casting.

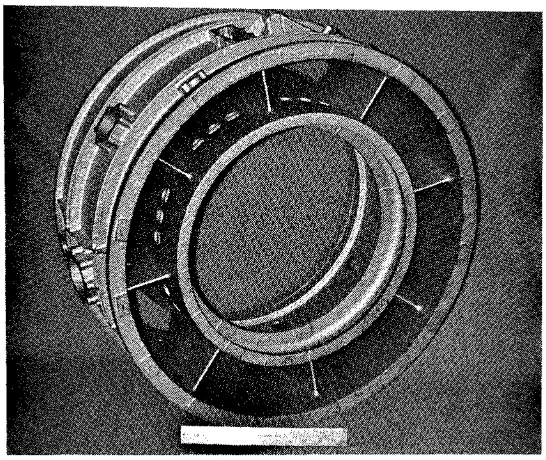

Fig. 5 MTU RB-199 intermediate case—large titanium investment casting.

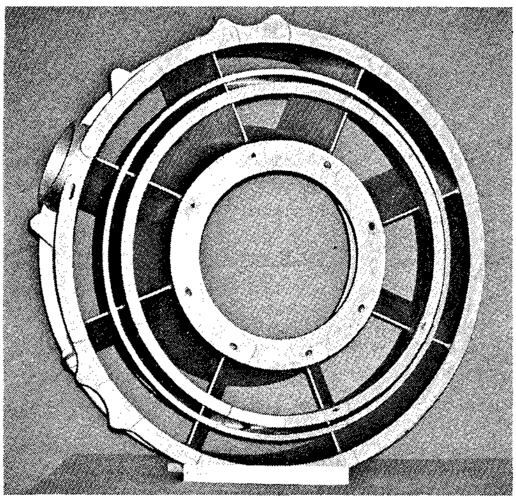

Fig. 6 Pratt & Whitney F100 intermediate case—large titanium investment casting.

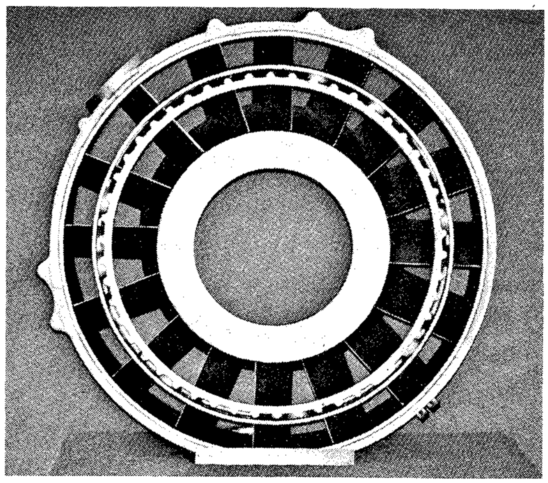

Fig. 7 Pratt & Whitney F100-II intermediate case—large titanium investment casting.

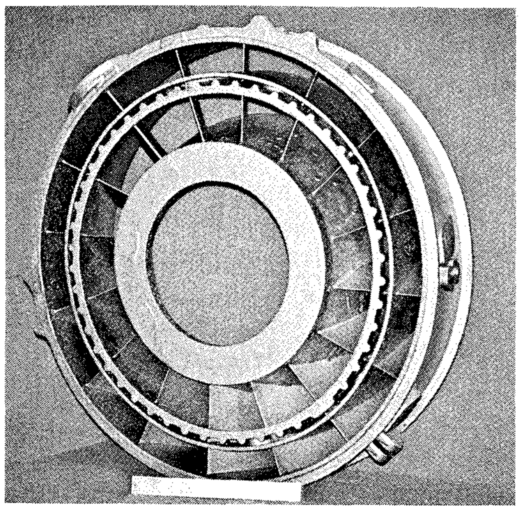

Fig. 8 Pratt & Whitney F100-II intermediate case—large titanium investment casting.

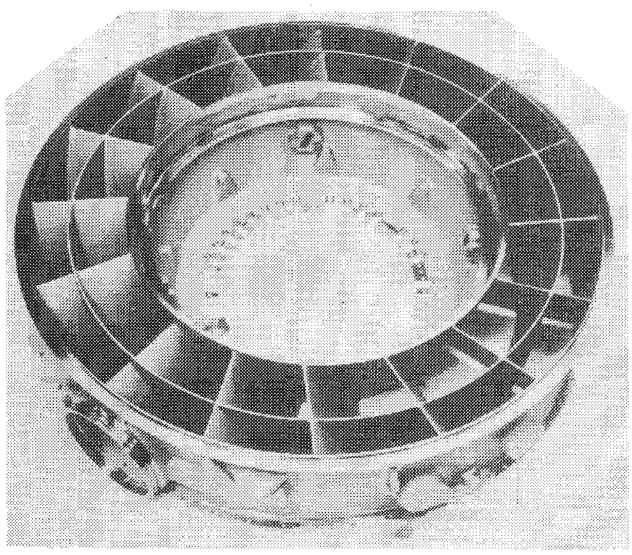

Fig. 9 Finished machined part Pratt & Whitney F100-II intermediate case—large titanium investment casting.

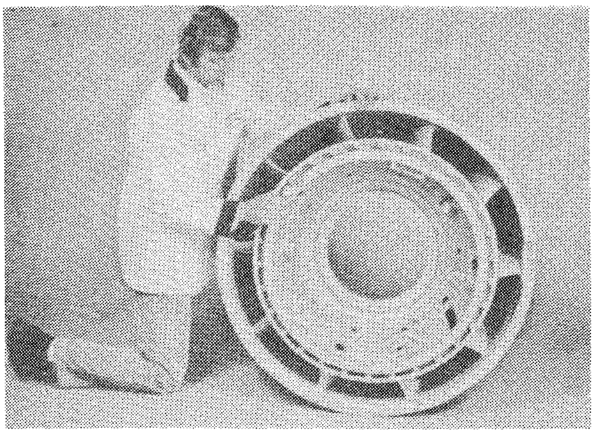

Fig. 10 Pratt & Whitney 2037 intermediate case—large titanium investment casting.

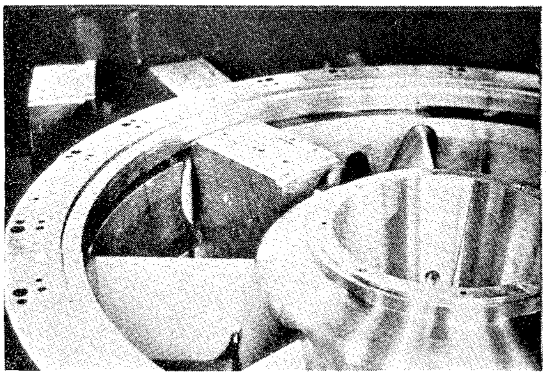

Fig. 11 Wax pattern tooling; F100 intermediate compressor case tooling.

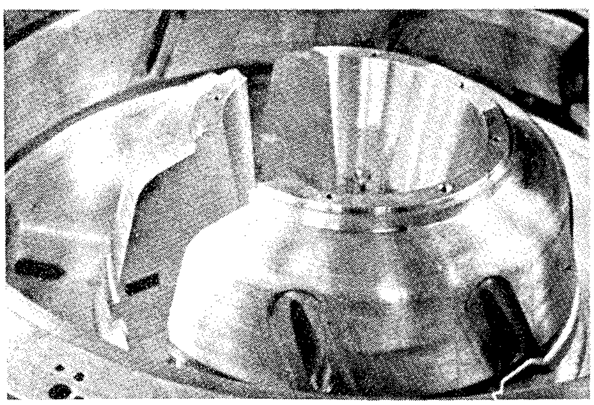

Fig. 12 Wax pattern tooling; six inside o.d. ring die blocks in place.

Current Casting Production

Precision Castparts Corp. (PCC) produces a wide range of investment castings, from just a few ounces to over 650 lb. Approximately 90% of the titanium castings produced at PCC are in the Ti-6Al-4V alloy. The remaining parts are in commercially pure titanium and a range of other alloys, including Ti 5-2.5, Ti 6-2-4-2, Ti 6-2-4-6, Ti 6-2-2-2-2, Transage 175, Ti_3Al, TiAl.

Figures 1-10 illustrate some typical cast components produced at PCC. Figures 1 and 2 illustrate some small components, including brackets, medical implants, and struts.

Figures 3-10 illustrate some large castings, including an inducer and four large structural components.

Figure 3 illustrates a large inducer produced for Rocketdyne. It is 26 in. in diameter and 16 in. high. Its weight is 300 lb. This part is utilized in a nuclear submarine for water torpedo ejection.

Figures 4 and 5 illustrate an intermediate compressor case casting produced for MTU. It is 29 in. in diameter and 14 in. high. Its weight is 105 lb. This part is utilized in the Rolls Royce RB-199 engine, which powers the NATO Panavia Tornado Aircraft.

Figure 6 illustrates an intermediate compressor case produced for Pratt & Whitney. It is 34 in. in diameter and 10 in. high. Its weight is 120 lb. This part was utilized experimentally in the F100 engine, which powers the F-15 and F-16 aircraft. Design changes precluded production use of the 8-strut version; however, the new Derivative II case is scheduled for production use.

Figures 7 and 8 illustrate the latest version intermediate compressor case for the F100 engine, also produced for Pratt & Whitney. It has the same dimensions and weight as the current configuration, but is a 16-strut version.

Figure 9 illustrates the finished, machined, 16-strut casting.

Figure 10 illustrates another intermediate compressor case casting produced for Pratt & Whitney. It is 40 in. in diameter and 13 in. high. Its weight is 235 lb. This part will be utilized in the 2037 engine, which will power the Boeing 757 commercial aircraft. Engine development and testing are underway at Pratt & Whitney with full production scheduled for 1984.

Not shown were a multitude of medium-sized components such as bearing housings and support castings, which PCC also produces. It should suffice to say that PCC produces the full gamut of precision investment castings from the smallest to the largest in the world.

Titanium Investment Casting Techniques

All of the parts shown were produced by the investment casting technique. It is a process that has been around for about 5000 years, but greatly refined in the last 20.

The investment casting process starts with a carefully tooled die, typically made of aluminum. Molten wax is injected into the die, producing an exact replica or pattern of the desired part. The wax pattern is dipped several times in a ceramic slurry, which hardens around it to form a shell called the investment. The wax is melted from the shell and a precise ceramic cavity remains. The shell is preheated, then loaded into a vacuum casting furnace. Titanium electrode stock is arc-melted into a water-cooled copper crucible and poured into the preheated shell. The shell is knocked off and the casting is cleaned, heat treated, inspected, and shipped to the customer.

Design Considerations

In addition to ensuring that the component will perform adequately in service, the designer must consider how the part will be produced. This is particularly true for titanium investment castings because casting parameters are quite limited. Metal superheat is not possible and mold preheat temperatures are limited by reactivity.

In definition of the casting envelope, the following should be considered and incorporated wherever possible: 1) smooth transitions between thick and thin sections; 2) generous fillets and radii; 3) tapered thin wall sections.

Another factor which must be considered is the specification of a casting envelope for which overly complex wax pattern tooling is not required. Tool makers are ingenious, but maximum cost effectiveness is usually achieved when the most straightforward tooling that will produce integral wax patterns is employed. The reasons for this emerge when a component having undercut features is considered. In order to remove the wax pattern from the tooling, multiple-die blocks must be used which require additional labor for

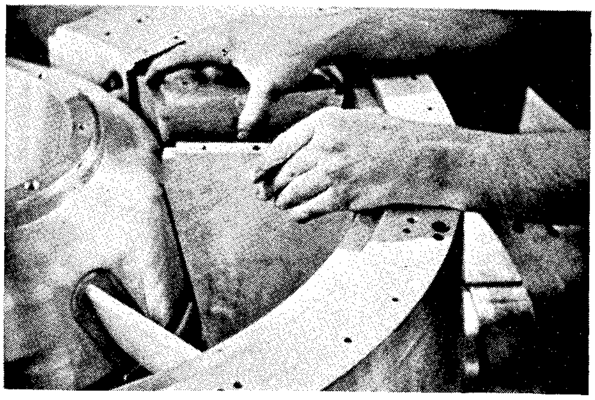

Fig. 13 Wax pattern tooling; strut die blocks positioned around soluble wax core.

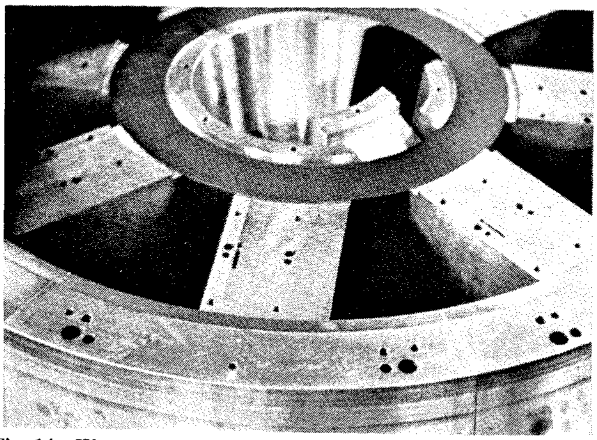

Fig. 14 Wax pattern tooling; removal of inside i.d. ring die blocks.

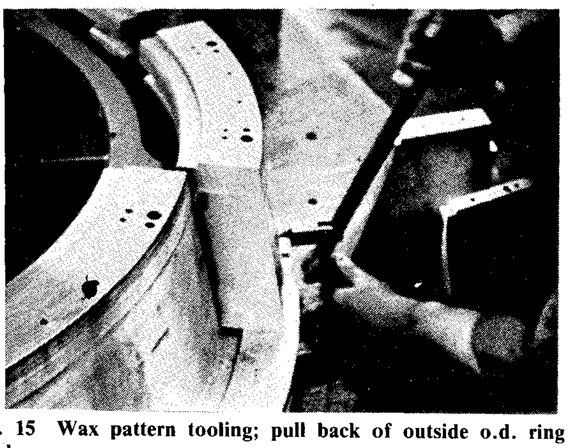

Fig. 15 Wax pattern tooling; pull back of outside o.d. ring die blocks.

assembly and disassembly for each pattern produced. Also, additional labor is required to inspect for, and remove any, wax flash resulting from the use of the multiple die blocks. Thus not only is the initial tooling cost increased, but each casting produced carries the increased cost of the additional labor. Another way in which undercut features can be obtained is to use two or more separate wax patterns and wax weld them together prior to investing. Here again, additional labor is required for each casting produced, and, unless extreme care is taken, the wax welds can introduce dimensional control problems and/or lead to shell defects which result in inclusions or gas porosity in the casting.

Figures 11-15 illustrate the wax pattern tooling for the Pratt & Whitney F100 Intermediate Compressor Case. The complexity of this tool is obvious, but it would have been even

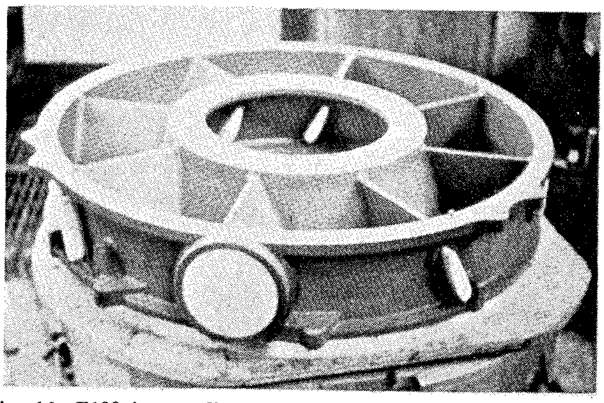

Fig. 16 F100 intermediate compressor case wax pattern showing gearbox opening.

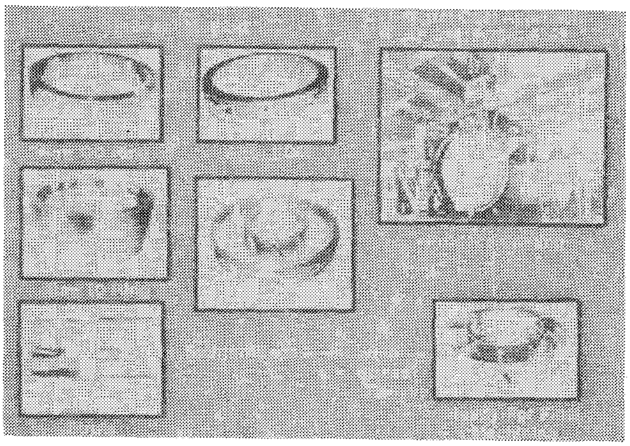

Fig. 17 Production method comparison; cast vs fabricated approach.

more complex, if P&W and PCC designers had not worked together in its design.

Figure 16 illustrates the wax pattern produced from the tool.

The definition of the casting envelope typically takes several iterations between the user and the casting source. It cannot be over-emphasized that the iterative approach to obtaining the optimum casting design is of utmost importance. The casting designer must assume that the engine designer's specifications are not flexible, if no communication exists between them. It is only through mutual understanding of performance requirements and casting limitations by both engine and casting designers that the most cost and performance effective configuration can be achieved.

Hot Isostatic Pressing (HIP)

A factor which should be considered in the design of a titanium casting is the utilization of HIP. The primary stumbling block for the acceptance of more castings in critical applications has been the high level of mechanical property data scatter which is typically encountered with cast material. While the average property levels of cast and wrought material are nearly equivalent, the minimum design levels are considerably lower for cast material because of the data scatter. Since the designer must use minimum design curves, wrought material is favored in most cases. This is where HIP comes in. The application of high temperature and inert gas pressure to castings produces a twofold change; the casting microstructure is homogenized and internal gas and shrinkage voids are eliminated. Both changes are advantageous in that they reduce mechanical property data scatter. HIP also allows production of components which are not castable from shrinkage and gas defect standpoints. Rejectable, internally defective cast components can be HIP processed into acceptable parts. Internal voids are transformed into dimples on the casting surface which are, in most instances, within blueprint requirements. The resultant part quality improvement with HIP is quite dramatic.

The most impressive quality improvements with HIP are noted on titanium castings. The consumable electrode arc-melting process, in which relatively low-pour temperatures are utilized, aids in production of sound casting skins which are required for HIP to be totally effective. To date, the majority of production HIP processing of castings has been on titanium alloy components.

Mechanical Properties

Comprehensive mechanical property test programs have been carried out on the MTU RB-199 and P&W F100 engine intermediate case castings, see Figs. 4 and 6. Numerous tensile and fatigue tests were performed on both thick and thin sections of the castings and the resultant mechanical properties were found to be excellent, typical of cast and hot isostatic pressed Ti-6Al-4V. The F100 engine intermediate case test results are presented in the final report for the AFML Titanium Alloy Engine Castings Program. The report number is AFWAL-TR-80-4157.

Cast vs Wrought Fabrication Economics

A one-piece casting offers distinct cost advantages over a wrought fabrication. Depending on the configuration and the extent of design interaction, the cost of a one-piece cast part will range from 15 to 35% lower than a wrought fabricated part.

Let us take another look at the F100 engine intermediate compressor case. Figure 17 shows a comparison between the cast and fabricated approaches. The fabricated part is constructed from massive rolled rings for the inner and outer flanges and bar stock for the struts. These must be machined and chemically milled prior to assembly and final machining. The weight breakdown for machining of the fabricated part shows that 1200 lb of wrought material are required to produce a 60-lb part, and that nearly 300 lb of the scrap is in the form of ECM sludge which is not economically recoverable. Material input for the cast part is 500 lb, much less than for the wrought part, and very little of the machining scrap is in the form of ECM sludge. Labor costs to achieve an engine-ready part are 50% lower for the cast part.

It obviously makes good economic sense to utilize large structural titanium castings.

The Future for Titanium Castings

The future for titanium castings, particularly large structural components, is bright. Reproducible casting processes have been established for a number of large structural titanium alloy castings.

The low material utilization factors and high machining costs for a great number of large structural engine and airframe wrought fabricated components represent a tremendous potential for cost reduction. The engine and airframe manufacturers are quickly replacing expensive wrought fabrications with large structural titanium castings.

Even more exciting though is the fact that new generation equipment is being designed initially with large structural titanium castings. A prime example is the Pratt & Whitney 2037 engine.

I predict that the use of large structural titanium castings will greatly increase for both military and commercial engine and airframe applications.