Thin Wall Titanium Structural CASTINGS

The development of thin-wall titanium castings was part of the Metals Affordability Initiative begun in 1999 by the Air Force Research Laboratory as an effort to reduce the cost of manufacturing metal components for aerospace applications.

David Lee,* Stewart Veeck*
Howmet Research Corp.
Whitehall, Michigan

Hsin-Nan Chou
Boeing-St Louis
St. Louis, Missouri

Jay Tiley *
AFRL/MLLM
Dayton, Ohio

Over the past several years, the Metals Affordability Initiative (MAI) has provided support for advanced processing technologies with the goal of reducing the cost of military aircraft and support systems. MAI efforts at Howmet and Boeing have been directed toward the production and implementation of thin-wall titanium alloy investment castings to replace components that currently are either machined or sheet metal fabrications.

The development studies involved concurrent engineering, solidification modeling, and designed casting experiments to develop strategies for producing thin-wall components. This article presents the results of the casting development activities, along with a description of the efforts required to implement this type of technology.

*Member of ASM International

MAI overview

MAI was created in 1999 by the Air Force Research Laboratory's Materials and Manufacturing Directorate (AFRL/ML). Its goal is to spur technology development aimed at lower-cost materials and manufacturing methods, efficient component designs, and tools and methods for reducing the time required for development and manufacturing. Fifteen companies, representing a cross-section of the complete aerospace metallic-component supply chain, have formed a consortium to address the technical issues.

Howmet Casting and Boeing–St. Louis have participated in the MAI program since its inception, with the specific goal of developing casting technology capable of producing thin-wall titanium aircraft engine and airframe structural components. In alignment with the MAI objectives, the primary goal of these efforts has been to reduce the cost of complex-geometry components that currently are fabricated from sheet or machined from bulk material.

More specifically, the program is designed to systematically address and defeat barriers to the application of thin-walled (0.035 to 0.050 in., 0.89 to 1.27 mm) cast components. This range represents a 30 to 50% reduction in the current state-of-the-art thin walls, in which the lower range of wall thickness is 0.060 to 0.080 in. (1.5 to 2.0 mm). In addition, a cost reduction of greater than 20% is to be demonstrated relative to the current Bill of Material (BOM). If these two primary criteria are met, then the final phase of the program will focus on implementation of the technology into production.

Fig. 1 — Components on the C-17 Globemaster transport were selected for evaluation.

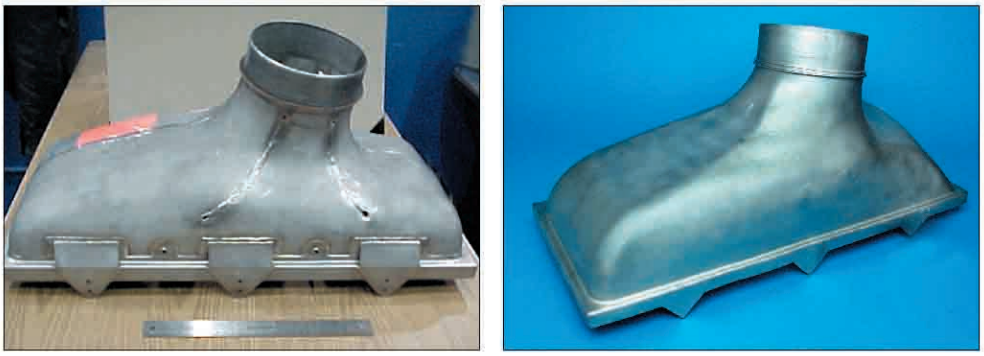

Fig. 2 — Pre-cooler plenum sheet metal assembly (left) and investment casting (right).

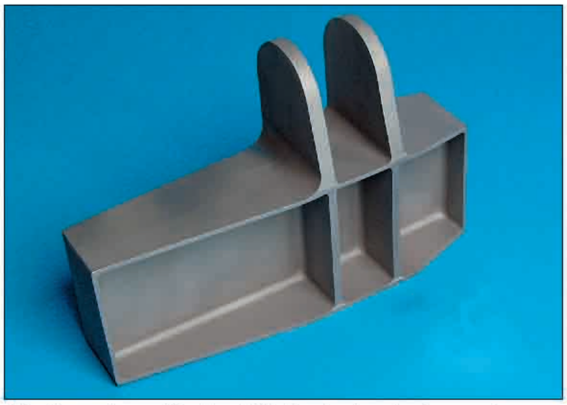

Fig. 3 — As-cast horizontal tail actuator clevis mount.

MAI procedures

Howmet, Boeing-St. Louis, and the Air Force Research Laboratory formed an Activity Integrated Product Team (AIPT) to identify and select suitable structural components for the planned thin-wall casting evaluations on the C-17 military transport. Candidate components were selected based on both potential cost reduction and geometric complexity factors.

Concurrent engineering of the selected components was then conducted to incorporate design features that would overcome the technical challenges. Solidification modeling also identified the optimal gating arrangement for several of the selected components.

Subsequently, key process variables were evaluated via designed experiments to optimize the potential for success. A number of the castings from the verification trials were selected for both preliminary static and dynamic mechanical property evaluations, as well as quality assessments. During each of the initial producibility demonstrations, Howmet and Boeing conducted a cost-benefit analysis to verify that cost reduction targets were being met. This analysis included an assessment of how pervasive the benefits of this technology would be to both military and commercial products.

Pre-cooler plenum

During the course of these efforts, several thin-wall components were evaluated. The initial feasibility efforts examined several components on the C-17 Globemaster Transport, shown in Fig. 1. The Pre-cooler plenum (Fig. 2), which directs cooling air within the engine pylon, was chosen as a demonstration vehicle for the initial casting evaluations. This component was being produced as a welded Ti-64 sheet metal fabrication made from multiple formed parts. The preliminary cost analysis suggested that producing it as a single piece casting could reduce the cost by ~35%. The nominal wall thickness of the part ranged from 0.040 to 0.060 in. (1.0 to 1.5 mm).

Molds for feasibility casting were made by stereolithographic apparatus (SLA). Several components were successfully produced by vacuum arc remelting (VAR) and casting. Solidification modeling did not reveal any potential issues of fill or residual shrinkage concentrations by the selected gating concept, and these results subsequently were validated by the casting efforts. After the chemical milling and repair welding operations were completed, the wall thickness of the cast parts had a nominal thickness of 0.040 to 0.060 in. (1.0 to 1.5 mm).

Although the casting efforts were a success, the final cost-benefit analysis indicated that the Pre-Cooler Plenum did not meet program objectives.

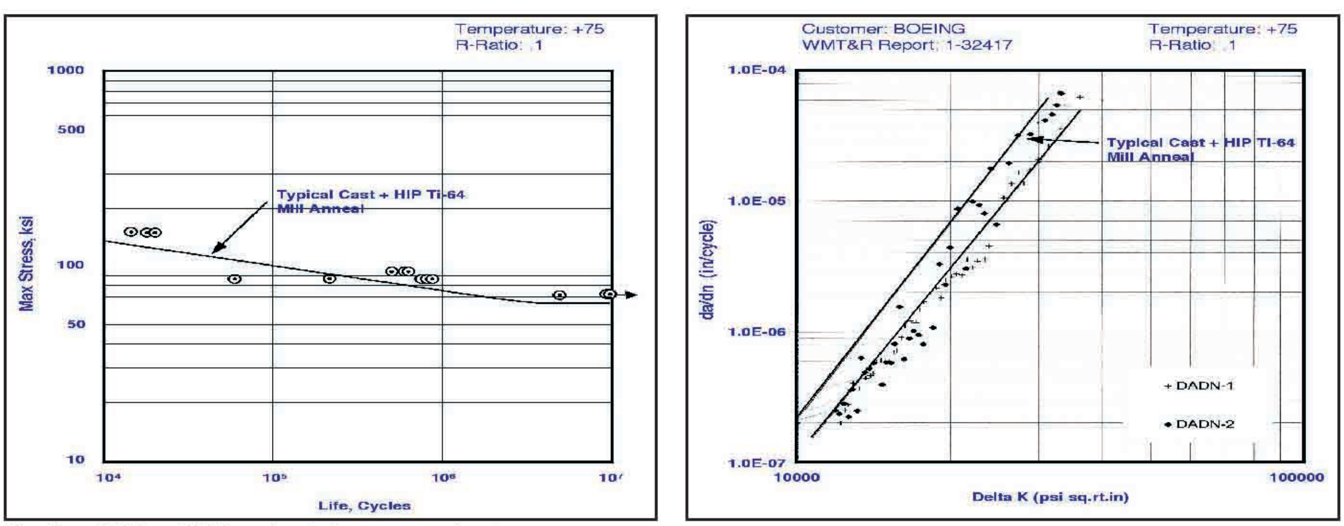

Fig. 4 — HCF and FCG mechanical property evaluations.

Table 1 — Tensile and fracture-toughness mechanical property evaluations

Alloy	Location	Average ultimate tensile strength, MPa (ksi)	Average yield strength, MPa (ksi)	Elongation, %	Fracture toughness, MPa $\sqrt{m}$ (ksi $\sqrt{in.}$)
Ti-6Al-4V	Web (0.1 in., 2.5 mm)	134 (1 9.4)	120 (17.4)	8.0	—
Ti-6Al-4V	Clevis (0.5 in., 12.7 mm)	133 (19.3)	120 (17.4)	10.6	108.3, 110.7 (97.5, 99.7)
Ti-6Al-4V	Mil-5 (0.75 in., 19 mm)	132 (19.1)	120 (17.4)	8.9	Typical 100 - 122 (90-110)
Ti-6242	Web (0.1 in., 2.5 mm)	151 (21.9)	127 (18.4)	9.0	—
Ti-6242	Clevis (0.5 in., 12.7 mm)	146 (21.2)	129 (18.7)	8.7	—
Ti-6242	Typical (cast)	152 (22.0)	132 (19.1)	12.6	—

The DOE experiment examined the casting thickness of the web, preheat temperature, mold insulation, face coat, and alloy.

Consequently, technical investigations were redirected toward a second, smaller part: a developmental JSF (Joint Strike Fighter) Horizontal Tail Actuator Clevis Mount under evaluation at Boeing-Seattle, Fig. 3. This fracture-critical component was to be BOM as-machined from plate, but it also met the Boeing castings design criteria.

Tail actuator component

The modeling data for the Horizontal Tail Actuator Clevis Mount component indicated that the part would marginally fill at an as-cast thickness of 0.10 in. (2.54 mm) in the web section, and that the web would be the controlling feature in terms of fill. The model also predicted distinct areas of potential HIP (Hot Isostatic Pressing) shrinkage, particularly at the radii located at the base of the interior pocket and at the radii in the base of the clevis attachments.

A modified L-16 DOE casting experiment was conducted with 1 x 3 molds representing each experimental condition. The gating concept was fixed, based on the initial modeling efforts.

The DOE experiment examined the casting thickness of the web, preheat temperature, mold insulation, face coat, and alloy. The alloy variable was added because the higher strength potential of Ti-6242 was of interest to Boeing; however, Ti-6242 also has reduced castability relative to Ti-64. The three parts from each casting trial were inspected for alpha case depth, flowlines/surface quality, HIP shrinkage/weld repair, and dimensional stability as metrics to evaluate the results.

Casting properties

All the components from the DOE were investment cast at Howmet's Ti-Cast operation located in Whitehall, Mich., and subsequently HIP'ed at 1650°F/15ksi/2h. Two features were worth noting in the initial castings:

- Only two cast components failed to completely fill in the web section (both were Ti-6242).
- Flowlines appeared to develop randomly in the web and side walls.

In addition, after HIP processing, almost all the castings exhibited some HIP shrinkage in the radii located at the base of the interior pocket or at the radii at the base of the clevis attachments. Clearly, these junctions, where four surfaces come together, represent a problem in terms of feeding adequately. HIP sink, which was also predicted by the solidification model, was also occasionally observed in the clevis near the tie bar or riser.

One part from each group of three castings was submitted for alpha case measurements. The remaining two underwent chemical milling, as well as a visual quality analysis and dimensional characterization after chemical milling. The target thickness in the web section after chemical milling was ~0.060 in. (1.5 mm). The alpha case data indicated that face coat, mold preheats, and mold wrap were the primary factors that controlled the formation of alpha case.

Higher preheats and mold wraps typically resulted in slower cooling of the mold after casting, and thus increased levels of alpha case formation. On the other hand, the visual quality was driven primarily by the alloy and web thickness of the part. Ti-6242 typically tends to have more gas defects and does not fill as well as Ti-64 alloy. The lower apparent quality of the parts with a thinner web may be a result of the higher potential of entrapment of gas defects caused by the higher solidification rate in the thinner cast parts.

Boeing and Howmet developed a mechanical property test matrix for HIP'ed and heat-treated cast components from the DOE test matrix. The Ti-64 parts were subjected to a standard 1550°F/2h mill anneal, while the Ti-6242 were treated by a duplex 1750°F/1h/GFC + 1150°F/2h heat treatment. All were evaluated by both tensile and dynamic tests. However, dynamic testing was restricted to the Ti-64 alloy only, and it included stress-controlled S/N fatigue testing, along with limited fracture toughness and fatigue crack growth (FCG) testing.

Tensile tests were conducted according to ASTM E-8 standard methods, while the fatigue tests were done in accordance with ASTM E-466. The fracture toughness and FCG tests were run on compact tension specimens, in accordance with ASTM E-399 and ASTM E-647, respectively. The dynamic test material for these evaluations was taken from the clevis areas of the castings. The results are provided in Table 1 and Fig. 4. Typical properties also have been included for comparative purposes.

Technology implementation

Having successfully demonstrated the technology to produce thin-wall cast titanium components with acceptable properties, the final phase of the program was directed toward implementation of the technology into production. The C-17 Engine Pylon Nose Cap and C-17 Engine Pylon Fire Seal were selected for the implementation efforts, because cost analyses for these cast components indicated a potential savings

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Fig. 5 — C-17 nose cap showing the fabricated assembly (left) and casting (right).

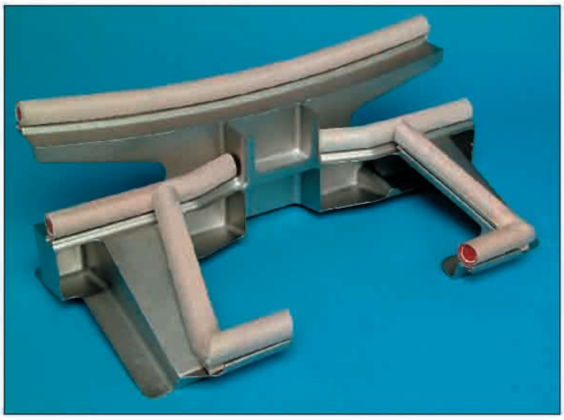

Fig. 6 — C-17 fire seal casting.

of ~40 to 70% over the BOM fabricated assemblies.

The C-17 Nose Cap fabricated assembly, consisting of 17 different Ti-64 pieces, and the initial cast component are shown in Fig. 5. The Nose Cap is the external cover for the engine pylon assembly, which provides aerodynamic flow for the pylon. The Boeing design group in St. Louis and Howmet titanium casting personnel initially conducted concurrent engineering studies to convert the part from a sheet metal built-up fabrication to a casting.

The nominal wall thickness of the casting produced by an SLA pattern, after chemical milling and repair welding, successfully met the dimensional target of 0.050 in. (1.27 mm), and the cast component fit the production fixtures at Boeing. The tube (made from Ti-64) was cast separately and welded into position. Because the casting provided both a reduction in cost and a modest weight reduction, Boeing has now proceeded to convert the component from a sheet metal fabrication to a casting.

However, implementation of the technology required a number of important steps, including casting design, stress analysis, and final approval by the Air Force. Concurrent with these activities, Boeing and Howmet jointly developed material and process specification requirements for the casting, including radiographic and fluorescent penetrant (FPI) inspections to identify possible inclusions and other defects.

An order for 60 production castings has been entered into the procurement system and a production wax tool has been fabricated. The new process will result in a potential cost savings of $3.2 million over the life of the project. Howmet currently is producing qualification pilot castings with final evaluation scheduled for Spring 2003, and planned incorporation of the castings into new aircraft beginning in Fall 2003.

The current C-17 Fire Seal also is a complicated structure consisting of multiple assemblies and fasteners. The component serves to seal the structural assembly from potential fires in the pylon. Each aircraft has a total of four seals. The proposed thin-walled Ti-64 casting is expected to reduce the cost associated with producing the part by over 70%. Figure 6 shows an initial C-17 Fire Seal casting produced from an SLA pattern based on electronic data from Boeing for the initial casting design.

The component currently is undergoing redesign to reduce weight further and to alter final configurations to fit changes in the connectors. The Project Team also is developing the qualification plan to ensure that the component exceeds material process and mechanical test requirements in accordance with Boeing specifications for investment castings. Implementation onto production aircraft is planned for Fall 2003.

The results of these studies suggest a number of opportunities to produce thin-wall titanium structural castings to replace sheet metal fabrications and/or machined components at a substantial cost saving. However, it is evident that these cost saving opportunities are maximized for more complex structures and assemblies. The technology to produce thin-wall titanium structures has been advanced during the course of these studies and the technology is available for production implementation as the opportunities present themselves. ■

References

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For more information: Stewart Veeck, Howmet Corp., 1500 Warner Street, Whitehall, MI 49461-1898; tel: 231/894-7206; fax: 231/894-7826; e-mail: sveeck@Howmet.com; Web site: www.Howmet.com.