Case Study: Additive Manufacturing of Aerospace Brackets

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Electron beam melting technology is a suitable additive manufacturing technology to produce complex aerospace components.

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Oak Ridge National Laboratory (ORNL) and Lockheed Martin recently demonstrated the capability of additive manufacturing technologies to drastically reduce the cost and material scrap associated with the production of aerospace components. Over the past decade, layered deposition techniques (i.e., rapid prototyping) transitioned toward a true manufacturing platform that can produce the form, fit, and function of a component. This approach, referred to as additive manufacturing (AM), demonstrates the ability to fabricate fully functional complex components at reduced production costs and significant material and energy savings. AM also has the potential to decrease component lead times and to fabricate complex designs not possible through conventional processing technologies. Metal AM technologies have not been widely adopted by the industrial sector partially because information pertaining to the mechanical integrity of components and the associated business case are not well understood. This article discusses a component that is well suited for production using metal AM techniques, demonstrates the mechanical properties of Ti-6Al-4V samples as a function of orientation and layout within the build chamber, and examines the associated business case for production.

Component selection
Application of metal AM has concentrated around components made of high-value materials such as Ti-6Al-4V or Ni-base superalloys because it increases material use and minimizes costly machining. A Bleed Air Leak Detect (BALD) bracket used in the hot side of the engine on Lockheed Martin’s Joint Strike Fighter platform was selected for this study. The BALD bracket is classified as a tertiary structure under light loading, which simplifies the certification process and increases the potential to implement AM technology into production. Traditionally, the BALD bracket is machined from wrought Ti-6Al-4V plate to the specified geometry. The bracket has a very thin cross section, resulting in a buy-to-fly ratio of 33:1; meaning 33 lb of raw stock plate is purchased to produce a 1-lb machined bracket. Because of these inefficiencies, AM was expected to be an attractive production method if the appropriate mechanical properties and cost structure could be achieved.

Electron beam melting
Electron beam melting (EBM), developed by Arcam AB (Mölndal, Sweden), is a powder-bed AM technology that fabricates fully dense metal parts by selectively melting specific regions within a 50-200 mm layer of powder. Successive layers are fused together to build up a near-net three-dimensional (3-D) structure. The process is conducted under vacuum to eliminate the potential for contamination/oxidation at elevated temperatures. Upon completion of the component, excess powder surrounding the solid structure is reclaimed and can be used in subsequent builds, which results in very limited waste for each component. An animation of the process can be found at http://www.ornl.gov/sci/manufacturing/video/direct_manufacturing.shtml.

The purpose of this work was to evaluate material properties as a function of location or orientation within the build chamber and to determine the economic feasibility of the EBM system for the BALD bracket. To go into production using EBM technology, it is essential that material properties are consistent and independent of orientation or location within the build chamber. This stems from the limited size of current system, requiring large parts to be oriented non-orthogonally to a primary axis within the chamber. Economic viability also requires that the number of parts included in the

Fig. 1 — Ti-6Al-4V bleed air leak detect (BALD) bracket fabricated using additive manufacturing.
build chamber be maximized. Thus, flexibility in orientation maximizes the number and type of parts that can be built using the Arcam process at minimized production costs.

The components for this study were fabricated at the Manufacturing Demonstration Facility at ORNL (www.ornl.gov/sci/manufacturing/mdf.shtml) using Arcam A2 direct manufacturing technology. The parts were made from Ti-6Al-4V powder provided by Arcam. Following EBM, components were hot isostatically pressed (HIPed) for two hours at a temperature of 1650°F and pressure of 15,000 psi. The surface finish associated with the EBM process is not suitable in the as-processed condition, so all components were oversized by 0.05 in. on all surfaces to allow for final machining. Tensile specimens were post-machined to ASTM E8 requirements while the BALD brackets and witness coupons were machined to a surface roughness of 125 rms.

Material properties

Figure 2 shows the layout of a build designed to investigate variation of mechanical properties, microstructure, and porosity with respect to location within the build chamber. Tensile samples produced as near-net-shape (NNS) and machined from large blocks were tested to determine the impact of the quantity of material on material properties. Most of as-deposited material was free of porosity, but voids as large as 300 mm were detected. HIP eliminated all porosity. The resulting microstructure is shown in Fig. 3.

Tensile tests were conducted on 50 samples from the build shown in Fig. 2. A total of seven and nine tensile samples were extracted from each vertical and horizontal block, respectively, and NNS samples were finish machined. Average tensile properties (Fig. 4) were 127-ksi yield stress, 137-ksi tensile strength, and 14.4% elongation.
at fracture. Although there is some variation in results, all tensile properties exceed ASTM specification for wrought Ti-6Al-4V plate material. Elongation values at break for NNS tensile bars are higher than those for samples extracted from vertical and horizontal blocks. Based on the results, it was determined that the Arcam EBM process is suitable to fabricate components requiring wrought Ti-6Al-4V tensile properties.

Bracket fabrication and testing

Nine BALD brackets were produced in a single build; the location and orientation of the brackets was varied within the build chamber (three groups at the center, corner, and edge) to determine the impact on mechanical properties (Fig. 5). Each group consisted of three brackets, oriented with the bracket web aligned with the x, y, and z-axes of the chamber. The layout was used for two builds having different powder compositions as shown in Table 1. Powder for the first build met AMS4928 chemical specifications. Powder for second run had higher oxygen content than allowed by specification.

Tensile test results are shown in Fig. 6. Yield and ultimate tensile stress were greater in samples with higher oxygen content, but both sample sets had similar total elongation. This result is only for simple tensile loading; it is expected that the higher oxygen content would negatively impact properties such as fracture toughness and fatigue. Because the design of the BALD bracket is limited by strength, mechanical properties were deemed adequate for production. Results also indicate that oxygen content below the ASTM specification for wrought material can be achieved using additive manufacturing techniques.

After EBM manufacturing and HIP, BALD brackets were machined (Fig. 7) and tested alongside unmachined brackets for comparison. Testing was conducted in a customized loading device where both tension and torsional forces were applied. Brackets were subjected to loading at a ten times factor of safety over service conditions. Permanent bending deformation of 0.03 in. occurred along the vertical web, but no brackets failed during testing despite repeated loading. The observed deformation is not enough to prevent brackets from serving their intended purpose and would not impact...
the system they support. There was no statistical difference in performance due to differences in surface finish, part orientation, or powder composition.

**Cost analysis for production**

The cost to fabricate a BALD bracket using EBM technology was directly compared to the current production method of machining the brackets from wrought plate. Wrought Ti-6Al-4V plate is significantly less expensive than spherical Ti-6Al-4V powder used in the EBM process, but the waste associated with machining complex geometries dominates manufacturing costs. Once scrap rate is included for the manufacture of a complex component, material costs can exceed $1000/lb of finished product. By comparison, the EBM process uses nearly 100% of the raw material and recovers any waste for recycling. This reduces the buy-to-fly ratio for the BALD bracket from 33:1 to just over 1:1. This study showed that using EBM technology (including HIP and final machining) would reduce current bracket cost by more than 50%.

**Conclusions**

EBM technology is a suitable additive manufacturing technology to produce complex aerospace components, such as the BALD bracket. As-deposited and HIPed brackets have consistent mechanical properties regardless of location or orientation within the build chamber, meeting the ASTM specification for wrought Ti-6Al-4V material for yield strength, ultimate tensile strength, and elongation. Component testing also satisfied the required mechanical performance for non-flight-critical hardware. Numerous brackets can be placed into the build chamber at various locations and orientations to maximize the production rate without sacrificing component quality. A simple cost analysis shows that EBM technology provides a 50% cost reduction over the current production method. Additional certification will be required prior to full production.

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