Titanium alloys are among the most important advanced materials and are key to improved performance in both aerospace and terrestrial systems, due to an excellent combination of specific mechanical properties and outstanding corrosion behavior\(^1\). However, widespread use is constrained by the high cost of titanium alloys compared to alternative materials\(^1\).

The high cost of producing conventional titanium components has spurred numerous investigations into potentially lower cost processes, including powder metallurgy (PM) near-net-shape techniques such as additive manufacturing (AM)\(^1\). This article reviews AM with an emphasis on the “work horse” titanium alloy, Ti-6Al-4V. AM is receiving significant attention from numerous organizations including the U.S. Navy, as it envisions use aboard carriers with parts able to be rapidly fabricated for immediate use by battle groups\(^2\). Various approaches to AM, along with examples of components made by different AM processes, are presented. The microstructures and mechanical properties of Ti-6Al-4V produced by AM are also discussed and compare well with cast and wrought products. Finally, the economic advantages of AM compared to conventional processing are presented.

**Additive manufacturing overview**

All AM technologies are based on the principle of slicing a solid model into multiple layers and building the part up layer by layer following the sliced model data. Following ASTM classification, AM technologies for metals can be broadly classified into two categories: directed energy deposition and powder bed fusion (Table 1). Several technologies fall under each category as branded by different manufacturers. While powder bed fusion

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* Member of ASM International

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**TABLE 1 — ADDITIVE MANUFACTURING TECHNOLOGIES FOR PROCESSING TITANIUM AND ITS ALLOYS**

<table>
<thead>
<tr>
<th>AM Category</th>
<th>Technology</th>
<th>Company</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Directed Energy Deposition (DED)</td>
<td>Direct Metal Deposition (DMD)</td>
<td>DM3D Technology LLC (formerly POM Group)</td>
<td>Laser and metal powder used for melting and depositing with a patented closed loop process.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Optomec Inc.</td>
<td>Laser and metal powder used for melting and depositing.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sciaky Inc.</td>
<td>Electron beam and metal wire used for melting and depositing.</td>
</tr>
<tr>
<td></td>
<td>Direct Metal Laser Sintering (DMLS)</td>
<td>EOS GmbH</td>
<td>Laser and metal powder used for sintering, melting, and bonding.</td>
</tr>
<tr>
<td></td>
<td>Laser Melting (LM)</td>
<td>Renishaw Inc.</td>
<td>Laser and metal powder used for melting and bonding.</td>
</tr>
<tr>
<td></td>
<td>Laser Melting (SLM)</td>
<td>SLM Solutions GmbH</td>
<td>Laser and metal powder used for melting and bonding.</td>
</tr>
<tr>
<td></td>
<td>LaserCUSING</td>
<td>Concept Laser GmbH</td>
<td>Laser and metal powder used for melting and bonding.</td>
</tr>
<tr>
<td></td>
<td>Electron Beam Melting (EBM)</td>
<td>Arcam AB</td>
<td>Electron beam and metal powder used for melting and bonding.</td>
</tr>
</tbody>
</table>
technologies enable construction of complex features, hollow cooling passages, and high precision parts, they are limited by the build envelope, single material per build, and horizontal layer construction ability. In comparison, directed energy deposition technologies offer larger build envelopes and higher deposition rates, but their ability to construct hollow cooling passages and finer geometry is limited. Direct metal deposition (DMD) and laser engineered net shaping (LENS) technology can deposit multiple materials in a single build and add metal to existing parts.

Commercially available AM technologies melt powder or wire feedstock using either laser or electron beam heat sources. Laser-based systems operate under inert atmosphere (for titanium processing) in contrast to the vacuum environment of electron beam systems. While vacuum systems are more expensive, they offer lower residual stress compared to laser-based systems, and electron-beam-processed parts can be used without stress relieving operations. Heat source effects on mechanical properties are discussed in more detail further in this article.

**Powder bed fusion**

Powder bed fusion technologies place a layer of metal powder on the build platform and then the powder is scanned with a heat source, such as a laser or electron beam, to either partially or completely melt the powder in the path of the beam and resolidify and bind it together as it cools (ASTM specification F2924-12a and -13 for Ti-6Al-4V and Ti-6Al-4V ELI grades, respectively). Layer-by-layer tool path tracing is governed by the CAD data of the part being built. Figure 1 shows a schematic explaining the steps involved in this process:

- A substrate is fixed on the build platform.
- The build chamber is filled with inert gas (for laser processing) or evacuated (for electron beam processing) to reduce the chamber’s oxygen level to the desired level.
- A thin layer of metal powder (20-200 mm thick, depending on the technology and equipment) is placed on the substrate and leveled to a predetermined thickness.
- The laser or electron beam scans the powder bed surface following the tool path precalculated from the CAD data of the component being built.
- This process is repeated for the following layers until the build is complete.

**Directed energy deposition**

Directed energy deposition technologies work by injecting material into a meltpool rather than scanning a powder bed (AMS specification 4999A for Ti-6Al-4V). Figure 2 shows a schematic of DMD technology (laser-based metal deposition). Steps for the directed energy deposition process include:

- A substrate or existing part is placed on the work table.
- Similar to powder bed fusion, the machine chamber is closed and filled with inert gas (for laser processing) or evacuated (for electron beam processing) to reduce the chamber’s oxygen level to the desired level (AMS 4999A specifies below 1200 ppm). The DMD process offers local shielding and does not require an inert gas chamber for less reactive metals than titanium, such as steels, Ni alloys, and Co alloys.
- At the start of the cycle, the process nozzle with a concentric laser or electron beam is focused on the part surface to create a meltpool. Material delivery involves powder traveling through a coaxial nozzle (laser) or through a metal wire with a side delivery (electron beam). The nozzle moves at constant speed and follows a predetermined toolpath created from the CAD data. As the nozzle (tooltip) moves away, the meltpool solidifies and forms a metal layer.
Successive layers follow the same principle and build up the part layer-by-layer. Table 2 provides a comparison of capabilities, benefits, and limitations of various AM technologies used for producing titanium parts[3-6].

### Titanium AM applications

Extensive exploration regarding use of AM titanium parts in aerospace and medical applications is underway. Other potential AM applications include the chemical and defense industries. While powder bed fusion technologies are suitable for smaller, complex geometries with hollow unsupported passages/structures, directed energy deposition is better suited for larger parts with coarser features requiring higher deposition rates.

Use of finer powder grains combined with smaller laser/electron beam size achieves a superior surface finish on the as-built parts from the powder bed fusion technologies compared to directed energy deposition technologies. However, the majority of AM parts require finish machining for most applications. Beyond building new parts, the ability of directed energy technologies to add metal onto existing parts makes it possible to apply protective surface coatings, remanufacture and repair damaged parts, and reconfigure or add features to existing parts.

### Complex geometry

A small beam size and small layer thickness, along with support of the powder bed, allow powder bed fusion technologies (such as EBM, DMLS, or SLS) to...
produce complex geometries with high precision and unsupported structures. Figure 3 shows an example of a hydraulic manifold mount for an underwater manipulator built using EBM technology. Building the integrated mount and manifold with internal passageways in a single operation eliminates fabrication of multiple parts and costs much less. A quality surface finish eliminates the need to machine finish all surfaces except seal surfaces and threading of screw holes. Generally, the PBF technique achieves a better surface finish than the DED approach, although demanding applications such as aerospace require finish machining. Figure 4 shows a biomedical implant built with a Ti-6Al-4V alloy using DMLS technology. These technologies also make it possible to build patient-specific custom implants.

Adding features to existing parts

Directed energy deposition technologies, such as DMD and/or LENS, can add metal to 3D surfaces to allow additional features to be added to existing parts and/or blanks, which is not possible using the PBF approach. Adding features to a forged or cast preform, as opposed to machining such features, can result in the most cost-effective manufacturing process, where a significant reduction of preform size and weight can be achieved by eliminating the need for a machining allowance. Examples include various casings and housings in jet engines where flanges and bosses can be added on cast or forged cylindrical preforms. To illustrate, Fig. 5 shows a feature added to a titanium fan casing for an aerospace engine.

Remanufacturing

One of the application areas best suited to directed energy deposition techniques is remanufacturing and repair of damaged, worn, or corroded parts. Due to the ability to add metal to select locations on 3D surfaces, these technologies can be used to rebuild lost material on various components. Closed loop technologies, such as DMD, achieve a minimum heat affected zone (HAZ) in the repaired part, which helps retain its integrity.

Figure 6 shows cross-section microstructures of the DMD area of a remanufactured turbine blade. Excellent process control during DMD leads to a fully dense microstructure as observed in the vertical cross-section. A layer thickness of roughly 0.1-0.2 mm was applied and a minimal HAZ occurs in the as-deposited blade. The DMD vision system plays a significant role in this type of remanufacturing application. An integrated, calibrated vision system allows automatic identification of part location in the machine coordinate system, resulting in precise processing. Other titanium components that can be repaired using DMD include housings, bearings, casing flanges, and landing gears.

Microstructure and mechanical properties

The Aerospace Materials Specification SAE AMS4999A covers Titanium Alloy Direct Products Ti-6Al-4V Annealed. This calls for a post-build annealing treatment of 1025°F (550°C). If a hot isostatic pressing (HIP’ing) treatment is used, it should be at no less than 14.5 ksi (100 MPa) within the 1650°-1750°F (899°-954°C) temperature range for 2-4 hours followed by a slow cool to below 800°F (427°C). Minimum tensile properties should be UTS 124-129 ksi (855-889 MPa, depending on direction), YS 110-116 ksi (758-800 MPa), and elongation of 6%.[10]

Typical microstructures of as-built material using the DMD process and after subsequent HIP’ing and aging are shown in Fig. 7. The as-built microstructure shows the typical martensitic structure expected for Ti-6Al-4V cooled rapidly from the beta phase field, while
the HIP’d and aged material shows the expected grain boundary of alpha and intergranular coarse alpha plates. This microstructural transition from as-deposited to the HIP’d-aged condition is also reflected through their tensile properties. While tensile strength and yield strength is a little lower after HIP’ing and aging, ductility improves significantly as a result of the microstructure changing from martensitic to a transformed beta (precipitated alpha) structure. As-built electron beam processed material contains a similar microstructure, although martensite is replaced by a lamellar alpha phase.

Tensile properties of Ti-6Al-4V fabricated by a number of additive manufacturing techniques are shown in Fig. 8. All processes achieve strength levels superior or comparable to conventional material (cast, forged, and wrought annealed). As-built materials in laser-based processes such as DMD, LENS, and DMLS exhibit less ductility due to formation of the martensite phase. However, ductility can be improved through subsequent HIP’ing and/or heat treatment. As a result of reduced residual stress, EBM-processed Ti-6Al-4V achieves greater ductility when compared to laser-processed Ti-6Al-4V. Fatigue properties were tested using many different cycles. In general, as-built Ti-6-4 offers fatigue resistance similar to cast and wrought material, even without HIP treatment, as shown in Fig. 9.

**Additive manufacturing economics**

Among the main benefits of powder bed fusion processes is their ability to create hollow structures and therefore achieve weight savings. The aerospace industry, where weight savings can make significant impacts, is actively looking into AM processes. A case study involving a seat buckle for commercial passenger jets is a prime example of this capability. A lightweight seat buckle with hollow structures was designed based on an extensive finite element analysis study to ensure adequate strength against shock loading. The part was produced using a DMLS Ti-6Al-4V alloy. Replacing a conventional steel buckle with a hollow AM titanium buckle achieves weight savings of 85 g per buckle, a 55% weight reduction. Applying this across an Airbus A380 with 853 seats results in weight savings of 72.5 kg. According to the project sponsor, Technology Strategy Board, UK, this weight savings translates to 3.3 million liters of fuel savings over the life of the aircraft, equivalent to $3 mil-
lion, while the cost of making the buckles using DMLS is only $256,000.

The direct manufacturing ability of AM technologies also helps reduce manufacturing costs in the case of high buy-to-fly ratio parts. For example, researchers at Oak Ridge National Laboratory built a Ti-6Al-4V Bleed Air Leak Detect (BALD) bracket for the Joint Strike Fighter (JSF) engine using EBM technology (Fig. 10)[14]. Traditional manufacturing from wrought Ti-6Al-4V plate costs almost $1000/lb due to a high (33:1) buy-to-fly ratio as opposed to just over 1:1 for the AM-built part. Estimated savings through AM is approximately 50%.

Direct deposition techniques such as DMD can not only be used to create parts, but these technologies can also be used for remanufacturing, repair, and/or feature building on existing parts. Damaged aerospace titanium components such as bearing housings, flanges, fan blades, casings, vanes, and landing gears can be rebuilt using these technologies at 20-40% of the cost of new parts[11]. Worn flanges in jet engine casings have been rebuilt using DMD at less than half the cost of new parts. Extensive work is also underway to investigate the feasibility of using such technologies to salvage components that are mismachined during conventional manufacturing. Successful realization of these efforts will have a significant impact on the titanium manufacturing industry. While most of the commercial activities in the AM industry are concentrated in the U.S. and Europe, significant efforts are underway in other parts of the world as well, including China[15].

Conclusions
Significant advances in additive manufacturing technologies over the past few years have led to the production of fully functional parts using titanium and its alloys. While powder bed fusion technologies offer the ability to build hollow near-net shapes with finer resolution, directed energy-based technologies offer the ability to add features to existing parts and remanufacture and repair damaged parts, besides building parts directly from CAD data. Most studies reveal that the properties of AM material are as good as, or superior to, conventionally fabricated titanium alloys. Matching the correct AM technology to the application, along with proper design optimization, can achieve significant savings by reducing both weight and scrap. The aerospace and medical industries have so far been the largest users of titanium AM materials, while other industries, such as automotive, are beginning to exploit the benefits of AM titanium alloys as well.

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Fig. 10 — BALD bracket for Joint Strike Fighter (JSF) built using EBM technology. Courtesy of ORNL.

References
15. Private communication, Ma Quin, July 2013.