

The additive manufacturing (AM) of titanium alloys

24

B. Dutta*, Francis H. (Sam) Froes**

*DM3D Technology, Auburn Hills, MI, USA

**Consultant to the Titanium Industry, Tacoma, WA, USA

24.1 Introduction

Titanium alloys are among the most important of the advanced materials that are key to improved performance in aerospace and terrestrial systems [1–5]. This is because of the excellent combinations of specific mechanical properties (properties normalized by density) and outstanding corrosion behavior [6–11] exhibited by titanium alloys. However, negating widespread use is the high cost of titanium alloys compared to competing materials (Table 24.1).

The high cost of titanium compared with the other metals shown in Table 24.1 has resulted in the yearly consumptions shown in Table 24.2.

In publications over the past few years [1–3], the cost of fabricating various titanium precursors and mill products has been discussed (very recently the price of TiO_2 has risen to \$2.00 per pound and TiCl_4 to \$0.55 per pound), and it has been pointed out that the cost of extraction is a small fraction of the total cost of a component fabricated by the cast and wrought (ingot metallurgy) approach (Figure 24.1). To reach a final component, the mill products shown in the figure must be machined, often with very high buy-to-fly ratios (which can reach as high as 40:1). The generally accepted cost of machining a component is that it doubles the cost of the component (with the buy-to-fly ratio being another multiplier in cost per pound) (Figure 24.2). This means that anything that can be done to produce a component that is closer to the final configuration will result in a cost reduction – hence the attraction of near-net-shape components.

The high cost of conventional titanium components has led to numerous investigations of various potentially lower cost processes [1–3], including powder metallurgy (PM) near-net-shape techniques [1–2,6–10,12,13]. In this chapter, one PM near-net-shape technique, additive manufacturing (AM), will be reviewed, with an emphasis on the “work horse” titanium alloy Ti-6Al-4V. This technique (described below) is receiving a lot of attention from the US Navy, who envision future use of the approach aboard a carrier where parts can be rapidly fabricated for immediate use on the battle group that the carrier is supporting [14]. The various approaches to AM are presented, followed by some examples of components produced by AM. The microstructures and mechanical properties of Ti-6Al-4V produced by AM are listed and shown to compare very well with cast and wrought product. Finally, the economic advantages to be gained using the AM technique compared to conventionally processed material are presented.

Table 24.1 Cost of titanium – a comparison*

Item	Material (\$/pound)		
	Steel	Aluminum	Titanium
Ore	0.02	0.01	0.22 (rutile)
Metal	0.10	1.10	5.44
Ingot	0.15	1.15	9.07
Sheet	0.30–0.60	1.00–5.00	15.00–50.00

*Contract prices. The high cost of titanium compared to aluminum and steel is a result of (a) high extraction costs and (b) high processing costs. The latter relates to the relatively low processing temperatures used for titanium and the conditioning (surface regions contaminated at the processing temperatures, and surface cracks, both of which must be removed) required prior to further fabrication.

Table 24.2 Metal consumption

Structural metals	Consumption/year (10 ³ metric tons)
Ti	50
Steel	700,000
Stainless steel	13,000
Al	25,000

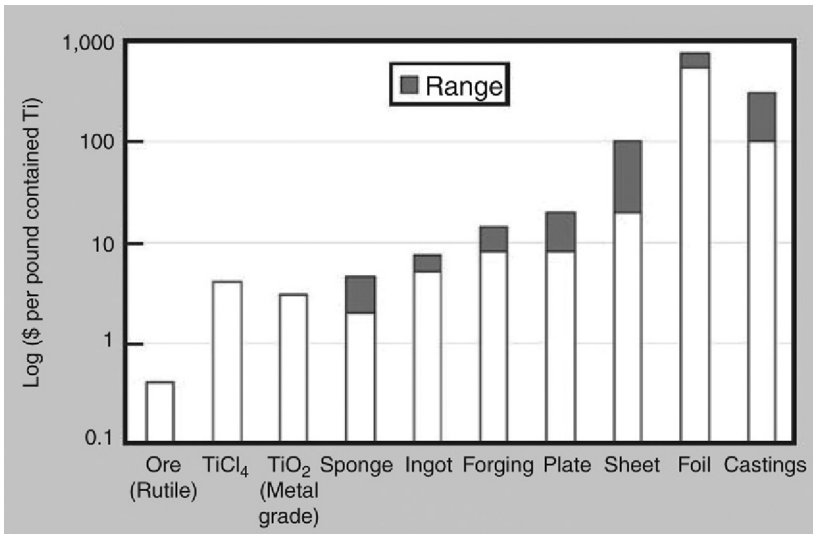


Figure 24.1 Cost of titanium at various stages of a component fabrication.

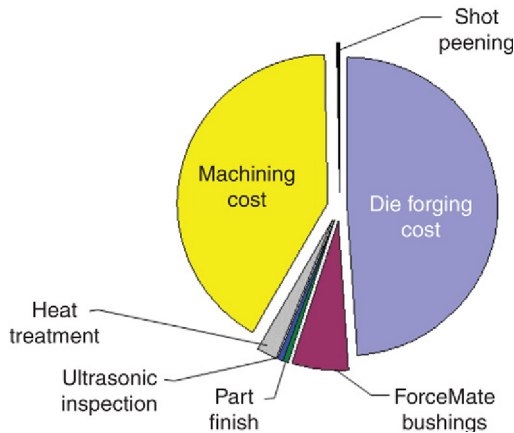


Figure 24.2 Boeing 787 side-of-body chord, manufacturing cost breakdown. (Courtesy Boeing.)

24.2 Technology overview

All the AM technologies are based on the principle of slicing a solid model in multiple layers to create a toolpath, uploading the data in the machine, and building the part up layer by layer following the sliced model data using a heat source (laser, electron beam, or electric arc) and feedstock (metal powder or wire). This section first addresses the creation of the computer toolpath and is followed by a discussion of the two broad classes of part-building technologies: powder bed fusion (PBF) and directed energy deposition (DED).

24.2.1 Software for AM

In principle, 3D printing is based on taking a 3D geometry, slicing it into multiple layers, and creating a toolpath that will trace the part layer by layer, one layer at a time. Three-dimensional printing of metals has its roots in stereo-lithographic process, invented by 3D Systems. Stereo lithography was built on a surface file format, called STL (Standard Tessellation Language) and widely used in rapid prototyping and computer-aided manufacturing. Many of the metal-based 3D printing technologies use STL files as input. Since STL represents the raw unstructured triangulated surface by the unit normal and vertices of the triangles using a 3D Cartesian coordinate system and does not contain any scale information, these files may not be suitable for complex operations and precision applications. Therefore, many AM technologies are using solid models as input. Remanufacturing and/or surface coating using deposition-based technologies (DED) poses additional challenges as it involves creating 3D layers as opposed to 2D layers for PBF technologies requiring five- or six-axis software for creation of toolpath. [Figure 24.3](#) shows a typical deposition path simulated on a computer-aided design (CAD) model for a 5-axis deposition process.

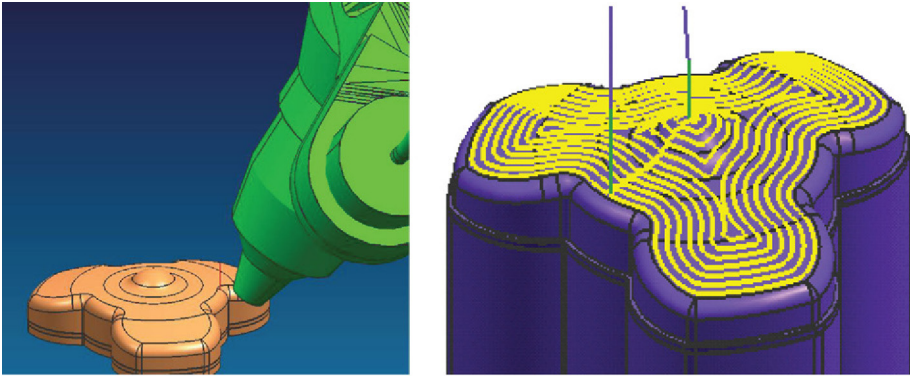


Figure 24.3 Left: CAD model of the part and process head. Right: Simulated toolpath for 5-axis deposition using DMDCAM software. (Courtesy DM3D Technology.)

24.2.2 Part-building technology

Following ASTM classification, AM technologies for metals can be broadly classified into two categories, DED and PBF (Table 24.3). There are several technologies under each category as branded by different manufacturers. While the PBF technologies enable building of complex features, hollow cooling passages and high precision parts, these are limited by build envelop, single material per build, and horizontal layer-building ability. In comparison, the DED technologies offer larger build envelop and higher deposition rate, while their ability to build hollow cooling passages and finer geometry is limited. DMD and LENS technology also offer the ability to deposit multiple materials in a single build and the ability to add metal on existing parts. Commercially available AM technologies are based on two types of heat sources, namely, laser and electron beam, for the purpose of melting the feedstock (powder or wire). Laser-based systems operate under inert atmosphere (for titanium processing) in contrast to the vacuum environment of the electron beam systems. While the vacuum systems are more expensive, they offer the advantage of low residual stress as compared to laser-based systems, and electron beam–processed parts can be used without any stress-relieving operation. The effect of the heat source on the microstructure and mechanical properties is discussed in more detail in sections 4.2 and 4.3.

24.2.2.1 Powder bed fusion

PBF technologies are based on the principles of laying down a layer of metal powder on the build platform and scanning the bed of powder with a heat source, such as laser or electron beam, that either partially or completely melts the powder in the path of the beam and the powder resolidifies and binds together as it cools off (ASTM specification F2924-12a and 13 for Ti-6Al-4V and Ti-6Al-4V ELI grade respectively). Layer-by-layer tool path tracing is governed by the CAD data of the

Table 24.3 Various AM technologies for processing of titanium and its alloys

AM category	Technology	Company	Description
Directed energy deposition (DED)	Direct metal deposition (DMD)	DM3D Technology LLC (Formerly POM Group)	Uses laser and metal powder for melting and depositing using a patented close loop process.
	Laser engineered net shaping (LENS)	Optomec, Inc.	Uses laser and metal powder for melting and depositing.
	Direct manufacturing (DM)	Sciaky, Inc.	Uses electron beam and metal wire for melting and depositing.
	Shaped metal deposition or wire and arc additive manufacturing (WAAM)	Not commercialized yet (patented by Rolls Royce Plc.)	Uses electric arc and metal wire for melting and depositing.
Powder bed fusion (PBF)	Selective laser sintering (SLS)	3D Systems Corp. (acquired Phenix Systems)	Uses laser and metal powder for sintering and bonding
	Direct metal laser sintering (DMLS)	EOS GmbH	Uses laser and metal powder for sintering, melting and bonding
	Laser melting (LM)	Renishaw Inc.	Uses laser and metal powder for melting and bonding
	Selective laser melting (SLM)	SLM Solutions GmbH	Uses laser and metal powder for melting and bonding
	LaserCUSING	Concept Laser GmbH	Uses laser and metal powder for melting and bonding
	Electron beam melting (EBM)	Arcam AB	Uses electron beam and metal powder for melting and bonding

part being built. [Figure 24.4](#) shows a schematic diagram 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 oxygen level in the chamber to the desired level.
- A thin layer of the metal powder (20–200 μm thick depending on the technology and equipment) is laid down on the substrate and leveled to a predetermined thickness using a leveling mechanism.

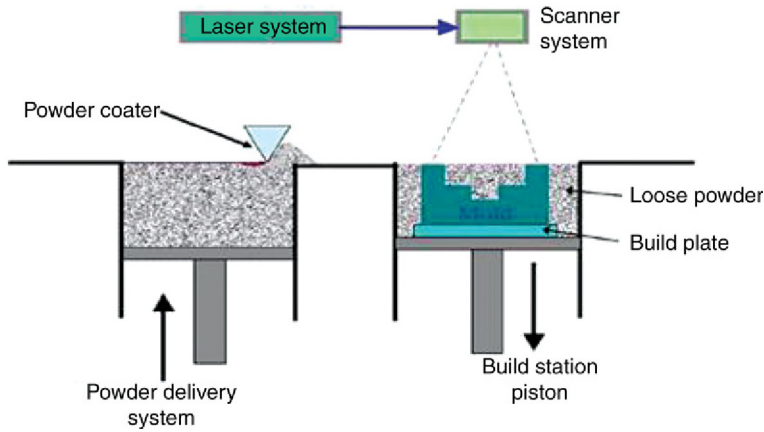


Figure 24.4 Schematic showing powder bed fusion technology. (Courtesy Jim Sears.)

- The laser or electron beam scans the powder bed surface following the toolpath precalculated from the CAD data of the component being built.
- The above process is repeated for the next and subsequent layer until the build is complete.

24.2.2.2 Directed energy deposition

DED technologies use material injection into the melt pool instead of scanning on a powder bed (AMS specification 4999A for Ti-6Al-4V). [Figure 24.5](#) shows a schematic of the DMD technology (laser-based metal deposition). The process steps for the DED are as follows:

- A substrate or existing part is placed on the work table.
- Similar to PBF, the machine chamber is closed and filled with inert gas (for laser processing) or evacuated (for electron beam processing) to reduce oxygen level in the chamber to the desired level (AMS 4999A specifies below 1200 ppm). The DMD process also offers local shielding and does not require inert gas chamber for less reactive metals than titanium, such as steels, Ni alloys, Co alloys, etc.
- At the cycle start, the process nozzle with a concentric laser or electron beam is focused on the part surface to create a melt pool. Material delivery is in the form of powder through a coaxial nozzle (for laser) or through a metal wire with a side delivery (for electron beam). The nozzle moves at a constant speed and follows a predetermined toolpath created from the CAD data. As the nozzle (tool tip) moves away, the melt pool solidifies forming a layer of metal.
- Successive layers follow the same principle and build up the part layer by layer until completion.

24.2.3 Technology comparison

[Table 24.4](#) below provides a comparison of capabilities, benefits, and limitations of various AM technologies that are used for producing titanium parts today.

[Figure 24.6](#) below shows a comparison of PBF technologies with DED technologies in terms of deposition rate and surface roughness. Note that the layer thickness

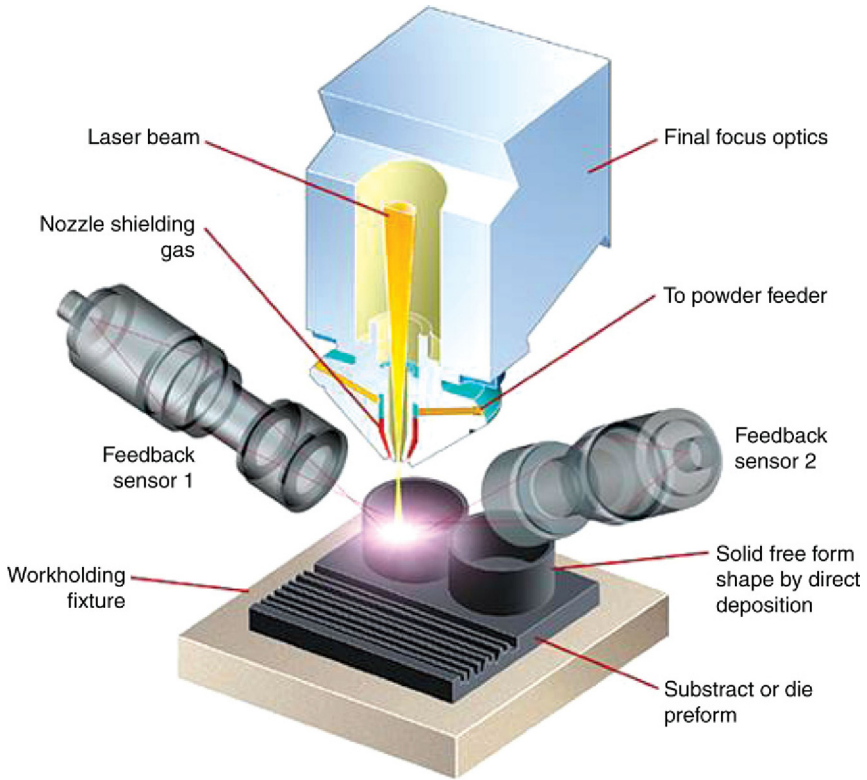


Figure 24.5 Schematic showing direct metal deposition (DMD) technology. (Courtesy DM3D Technology.)

has been used as a measure of roughness here as this determines the roughness of the vertical walls of the structure being built. Clearly, the PBF technologies offer better surface finish as these use smaller beam size (for both laser and electron beam) and smaller layer thickness as compared to DED technologies; however, as a consequence the deposition rate is also lower for these technologies. Therefore, PBF is more suitable for more accurate, complex, small-size objects, while DED is more suitable for building relatively larger parts at a high processing rate, but with coarser finish surface.

24.3 Titanium AM applications

Extensive exploration is currently underway for usage of AM titanium parts in aerospace and medical applications. Other applications for AM include applications in chemical, defense, and other industries. While PBF technologies are suitable for smaller, complex geometries, with hollow unsupported passages/structures, DED is better suited for larger parts with coarser features requiring higher deposition rates. Usage of finer powder grains combined with smaller laser/electron beam size leads to

Table 24.4 Comparison of various technologies [15–18]

Item	Laser based PBF (e.g., DMLS)	Electron beam based PBF (e.g., EBM)	Laser based directed energy deposition (e.g., DMD)
Build envelop Beam size	Limited Small, 0.1–0.5 mm	Limited Small, 0.2–1 mm	Large and flexible Large, can vary from 2–4 mm
Layer thickness Build rate Surface finish	Small, 50–100 μm Low, cc/h Very good, Ra 9/12 μm , Rz 35/40 μm	Small, 100 μm Low, 55–80 cc/h Good, Ra 25/35 μm	Large, 500–1000 μm High, 16–320 cc/h Coarse, Ra 20–50 μm , Rz 150–300 μm , Depends on beam size
Residual stress Heat treatment	High Stress relieve required, HIPing preferred	Minimal Stress relieve not required, HIPing may or may not be performed	High Stress relieve required, HIPing preferred
Chemistry	ELI grade possible, negligible loss of elements	ELI grade possible, loss of Al need to be compensated in powder chemistry	ELI grade possible, negligible loss of elements
Build capability	Complex geometry possible with very high resolution Capable of building hollow channels	Complex geometry possible with good resolution Capable of building hollow channels	Relatively simpler geometry with less resolution. Limited capability for hollow channels, etc.
Repair/ remanufacture	Possible only in limited applications (requires horizontal plane to begin remanufacturing)	Not possible	Possible (capable of adding metal on 3D surfaces under 5 + 1-axis configuration, making repair solutions attractive)
Feature/metal addition on existing parts	Not possible	Not possible	Possible. Depending on dimensions ID cladding is also possible
Multimaterial build or hard coating	Not possible	Not possible	Possible

a superior surface finish on the as-built parts from the PBF technologies as compared to DED technologies. However, majority of the AM parts need finish machining for most of the practical applications. Ability of the directed energy technologies to add metal on existing parts allow them to apply surface protective coatings, remanufacture and repair of damaged parts, and reconfigure or add features to existing parts, besides building new parts.

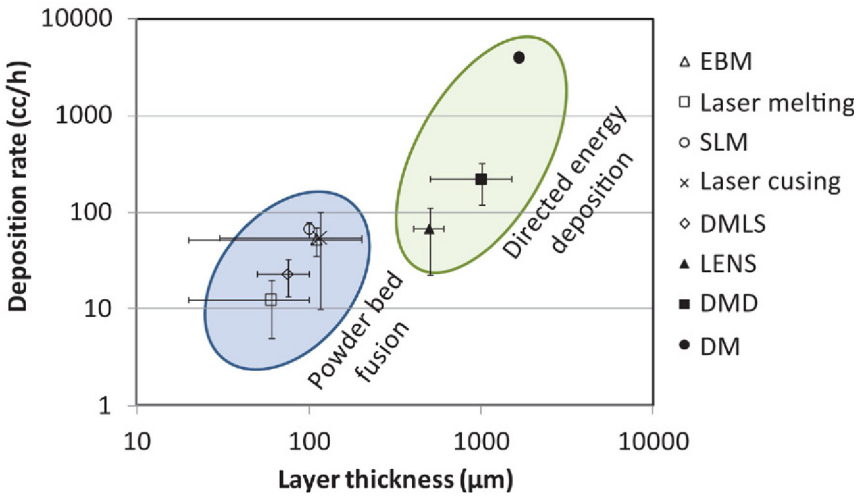


Figure 24.6 Comparison of PBF and DED technologies in terms of layer thickness and deposition rate [15,19–24].

24.3.1 Complex geometry

Small beam size and low layer thickness along with support of the powder bed allow PBF technologies, such as electron beam melting (EBM), direct metal laser sintering (DMLS), or selective laser sintering (SLS), to produce complex geometries with high precision and unsupported structures. Figure 24.7 shows one such example of

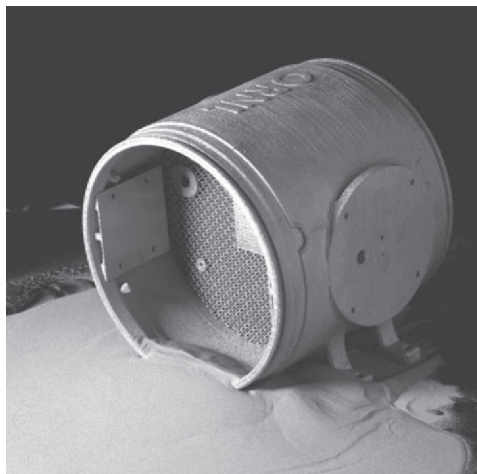


Figure 24.7 Hydraulic manifold built using EBM technology. The part was built at the MDF in Oakridge National Laboratory through an ONR-sponsored project. (Courtesy ORNL, TN.)



Figure 24.8 Medical implant application using; (a) DMLS technology. (Courtesy Jim Sears.) (b) EBM technology [26].

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 multiple part fabrication and effects significant cost savings. Good surface finish of the part eliminated finish machining needs on all surfaces, except seal surfaces and threading of screw holes. Generally the PBF technique gives a better surface finish than the DED approach; however, for demanding applications such as aerospace, finish machining is required [25].

Figure 24.8a shows an example of a biomedical implant built with Ti-6Al-4V alloy using DMLS technology, while Figure 24.8b shows a tibial (knee) Ti6Al4V stem built using EBM technology. These technologies also have the potential of building patient-specific custom implants to better suit the needs.

24.3.2 Feature addition

DED technologies, such as, DMD and/or LENS have the ability to add metal on 3D surfaces and, thus, allow addition of features on existing parts and/or blanks. This is not possible with the PBF approach. Adding features to a forged or cast preform as opposed to machining of such features can provide the most cost-effective manufacturing option, where a significant reduction of the preform size and weight can be effected through the elimination of the need for a machining allowance. Examples are various casings and housings in jet engines where flanges, bosses, etc. can be added on cast or forged cylindrical preforms. This is demonstrated for a feature addition on a titanium fan casing for an aircraft engine (Figure 24.9).

24.3.3 Remanufacturing

One of the best application areas suited for DED techniques is remanufacturing and repair of damaged, worn-out, corroded parts. Because of their ability to add metal on select locations on 3D surfaces, these technologies can be used to rebuild lost material



Figure 24.9 Fan case produced by adding features with AM (laser-aided directed energy deposition) to a forged perform. (Courtesy Jim Sears.)

on various components [27–29]. Closed-loop technologies, such as DMD, offer the particular benefit of a minimum heat-affected zone (HAZ) in the repaired part and helps to retain the integrity of the part. The closed-loop control allows DMD to repair parts with short HAZ and produce a high-quality repaired part. Figure 24.10 shows cross-sectional microstructures of the DMD area of a remanufactured turbine blade.

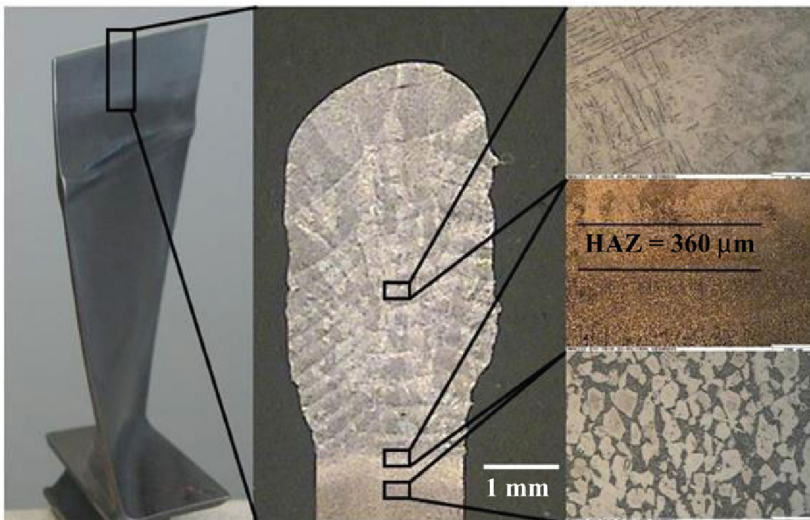


Figure 24.10 DMD repair of turbine components; left: repaired vane, middle: macro cross section, and right: microstructures (top to bottom shows the clad, interface, and base material). (Courtesy DM3D Technology.)

The excellent process control during DMD leads to a fully dense microstructure as observed in the vertical cross section. A layer thickness of about 0.1–0.2 mm has been applied in this case and a minimal HAZ is observed in the as-deposited blade. DMD vision system plays a significant role in this type of remanufacturing applications. A calibrated vision system integrated with the machine allows automatic identification of part location in the machine coordinate system and precision processing. Other titanium components that can be repaired include housings, bearings, casing flanges, seals, landing gears, etc.

24.4 Microstructure and mechanical properties

24.4.1 Specifications

The Aerospace Materials Specification SAE AMS4999A covers Titanium Alloy Direct Products Ti-6Al-4V Annealed. This calls for a postbuild annealing treatment of 550°C (1025°F) and if a HIPing treatment is used, it should be at not less than 100 MPa (14.5 ksi) within the range 899–954°C (1650–1750°F) for 2–4 hours followed by a slow cool to below 427°C (800°F). Minimum tensile properties shall be ultimate tensile strength (UTS) 855/889 MPa (124/129 ksi) (depending on direction), yield strength (YS) 758/800 MPa (110/116 ksi), and elongation of 6% [30].

24.4.2 Microstructures

Microstructure of the additively manufactured titanium is very different from that of a wrought product. With suitable post-processing, additively manufactured titanium can exhibit equivalent or better mechanical property than a conventionally manufactured titanium part.

Figure 24.11 shows typical microstructures of as-built Ti6Al4V alloy from various AM processes. Corresponding tensile properties (UTS and YS) are also plotted as a function of elongation to show the effect of microstructure on mechanical properties. Clearly, laser-based technologies offer higher strength and lower ductility because of the formation of α' -martensite as a result of fast cooling. Electron beam processed material exhibit α - β microstructure due to slower cooling in vacuum atmosphere and results in lower tensile strength and higher ductility. In comparison, microstructure morphology is coarser in the as-cast material and wrought material has equiaxed α - β microstructure. Arc-processed material (wire and arc AM [WAAM]) offers a microstructure similar to cast structure, though finer in length scale. The effect of these various microstructures is well demonstrated in their tensile behavior.

Figure 24.12 shows microstructure of as-built material using DMD process and after subsequent HIPing (hot isostatic pressing) and aging. The as-built microstructure shows the typical martensitic structure expected for Ti-6Al-4V cooled rapidly from the beta phase field, while the HIPed and aged material shows the expected grain boundary alpha and intergranular coarse alpha plates. This microstructural transition from as-deposited to HIPed-aged condition is also reflected through their tensile properties. While UTS and YS is a little lower after HIPing and aging, ductility improves significantly (see below) as a result of the microstructure changing from martensitic to transformed beta (precipitated alpha) structure.

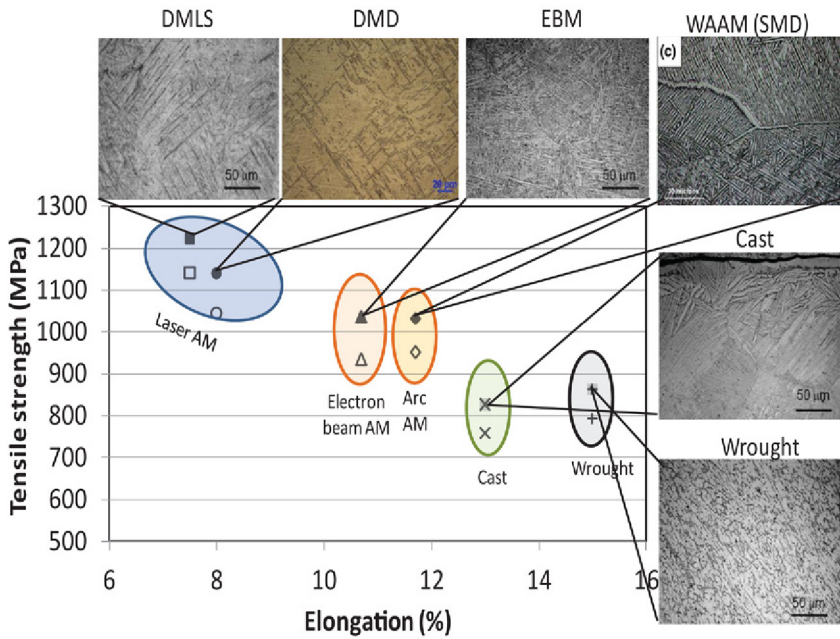


Figure 24.11 Room-temperature tensile behavior of AM Ti6Al4V alloy produced using various AM technologies and their comparison with cast and wrought material properties [18, 19, 31–33]. Typical microstructures are also included for comparison. Closed and open symbols represent UTS and YS respectively.

24.4.3 Mechanical properties

Tensile properties of Ti-6Al-4V fabricated by a number of AM techniques are shown in Figure 24.13. All of the processes show strength levels superior or comparable to conventional material (cast, forged, and wrought-annealed). As built materials in

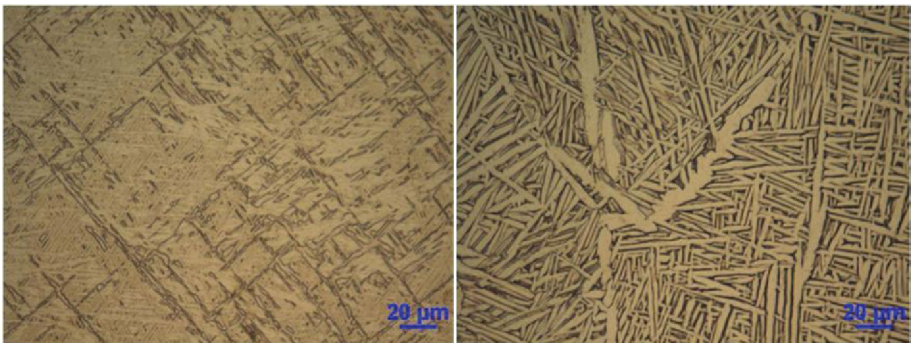


Figure 24.12 Microstructure of DMD built Ti6Al4V before and after HIPing. (Courtesy DM3D Technology.)

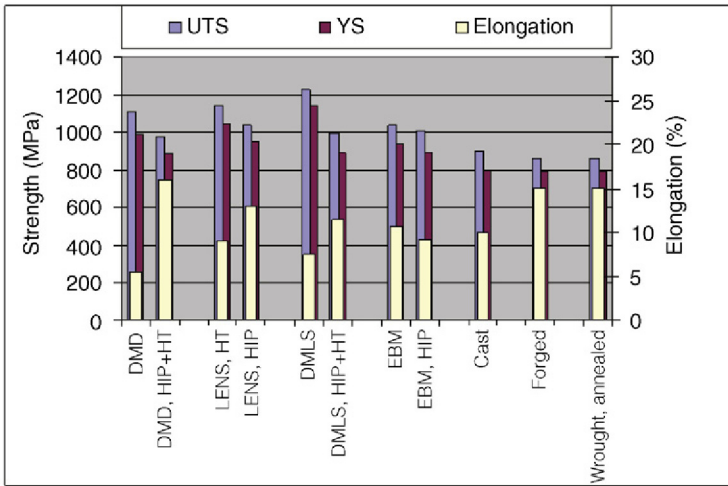


Figure 24.13 Tensile strength, yield strength, and elongation of Ti-6Al-4V alloy built using various AM processes. DMD, direct metal deposition [19]; LENS, laser engineered net shaping [21]; DMLS, direct metal laser sintering [18]; EB, electron beam melting [18]; HIP, hot isostatic pressing; HT, heat treatment.

laser-based processes, such as DMD, LENS, and DMLS, exhibit less ductility because of the formation of the martensite phase; however, the ductility can be improved through subsequent HIPing and/or heat treatment operation. As a result of reduced residual stress, EBM processed Ti-6Al-4V shows greater ductility when compared to laser processed Ti-6Al-4V. Fatigue properties have been tested using many different cycles. In general, as built Ti-6-4 offers fatigue resistance similar to cast and wrought material, even without a HIP treatment. (Figure 24.14).

DED technologies offer the benefit of repair and remanufacture of damaged parts as well as feature addition on existing parts and performs (such as castings, extrusions, forgings). Therefore, it is of considerable interest to examine properties of such repairs and feature additions. Figure 24.15 shows that “V” groove-repaired and “slot”-repaired Ti6Al4V samples exhibit comparable tensile strength with nonrepaired wrought Ti6Al4V sample. These samples were repaired using DMD technology and represent repairs done in the seal areas of jet engine components, such as casings and housings [19]. Ti6242 samples repaired using laser cladding has shown higher high cycle fatigue strength than wrought Ti6242 material [34].

24.5 Economics of AM

Figure 24.16 shows a typical cost breakdown of various steps involved in AM of titanium components based on the following assumptions: (a) small batch size (between 10 and 30 parts), (b) medium-size part, ~600–900 mm (2–3 ft) in size and relatively simple geometry. It is to be noted that any and all of these factors can significantly

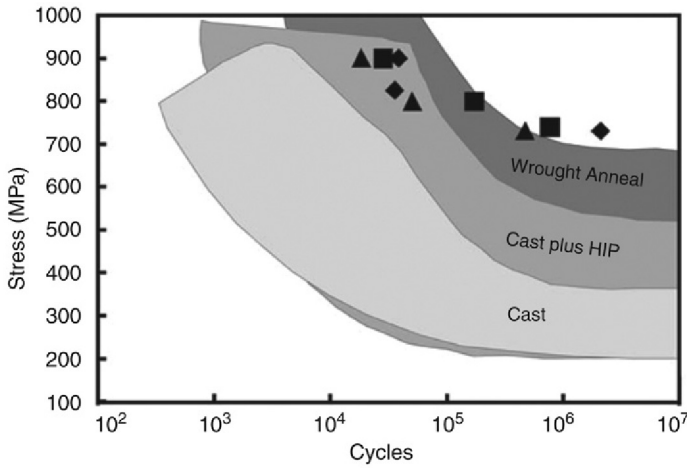


Figure 24.14 Comparison of room temperature fatigue properties of AM-fabricated Ti-6Al-4V and conventionally fabricated Ti-6Al-4V. ■, ◆, and ▲ represent properties in the three orthogonal directions *x*, *y*, and *z*, respectively. (Courtesy EADS/Jim Sears.)

influence the cost. The batch size plays a major role in costing for small batch sizes, while part size plays a more significant role in costing for larger batch sizes. Benefits of tool-less manufacturing make AM as an attractive manufacturing option for small batch sizes when compared with conventional manufacturing techniques, such as casting, forging, extrusion, etc. However, relatively lower throughput renders AM less attractive for high-volume manufacturing [35].

Success of expanding AM in the manufacturing industry depends on the selection of right applications. Value-added AM applications include long lead time complex components, weight savings, cost-effective remanufacturing, customized medical

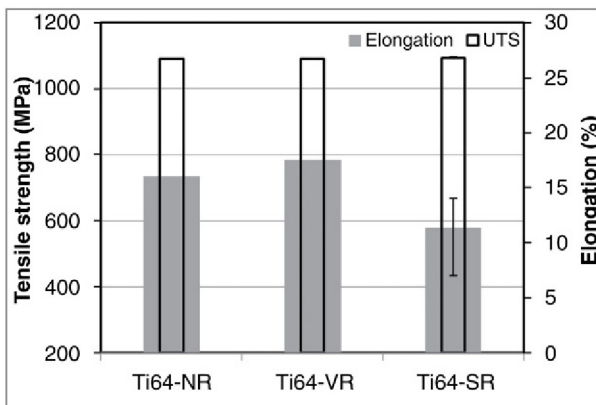


Figure 24.15 Mechanical behavior of DMD-repaired Ti6Al4V alloy. NR represents nonrepaired material, while VR is a “V” groove-repaired material and “SR” is slot-repaired material.

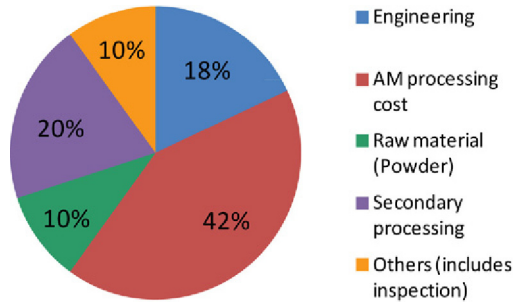


Figure 24.16 Typical cost breakdown of various steps involved in AM of titanium

implants, multimaterial components, etc. Below are few case studies that elaborate more on these aspects of AM.

One of the major benefits of the PBF processes is their ability to create hollow structures and, thereby, allow weight savings. Aerospace industry, where weight savings can have very significant impact, is actively looking into this ability of AM processes. A case study involving a seat buckle for commercial passenger jets is a perfect example of this [36]. A lightweight seat buckle with hollow structures was designed based on extensive FEA study to ensure enough strength against shock loading. The part was produced using DMLS Ti-6Al-4V alloy (Figure 24.17). Replacement of a conventional steel buckle with hollow AM titanium buckle causes 85 g weight saving per buckle (55% weight reduction). An Airbus A380 with 853 seats will result in a possible weight saving of 72.5 kg. According to the project sponsor, Technology Strategy Board, United Kingdom, this weight saving translates to 3.3 million liters of fuel saving over the life of the aircraft that is equivalent to £2 million (\$3 million), while cost of making all the buckles using DMLS is only £165,000 (\$256,000).

The direct manufacturing ability of AM technologies also helps to reduce manufacturing costs in the case of high buy-to-fly ratio parts. Researchers at the Oakridge

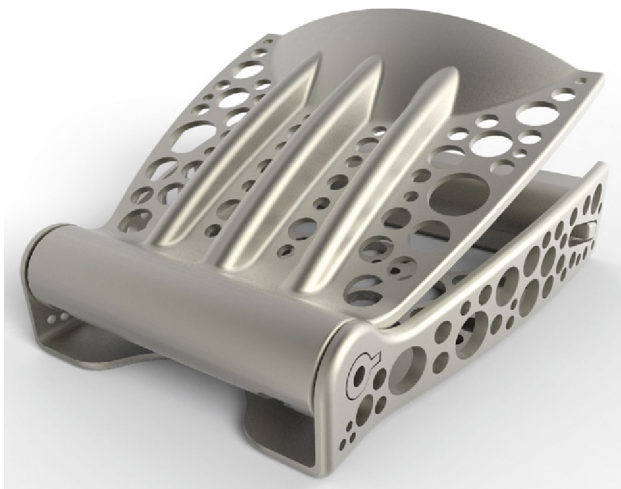


Figure 24.17 Seat buckle produced using DMLS technology.



Figure 24.18 BALD bracket for Joint Strike Fighter (JSF) built using EBM technology. (Courtesy ORNL, TN.)

National Laboratory built a Ti-6Al-4V Bleed Air Leak Detect (BALD) bracket for the Joint Strike Fighter (JSF) engine using EBM technology (Figure 24.18)[25]. Traditional manufacturing from wrought Ti-6Al-4V plate costs almost \$1000/lb because of a high (33:1) buy-to-fly ratio as opposed to just over 1:1 ratio for the AM built part. Estimated saving through AM is about 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 expensive aerospace titanium components, such as bearing housing, flanges, fan blades, casings, vanes, landing gears, etc., can be rebuilt using these technologies at 20–40% of the cost of the new parts [19]. Worn-out flanges in jet engine casings have been rebuilt using DMD at less than half of the cost of a new part. Extensive work is 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 very significant impact on the titanium manufacturing industry. While most of the leading commercial activities in the AM industry is concentrated in USA and Europe, significant efforts are underway in many parts of the world, including China [37].

24.6 Research and development

The vast majority of Ti AM components have been fabricated using high-cost spherical gas atomized or plasma rotating electrode process (PREP) powder. As seen in Figure 24.16, the raw material (mostly powder) cost can be almost 10% of the overall component cost. As AM continues to evolve, focus is on driving the powder cost down

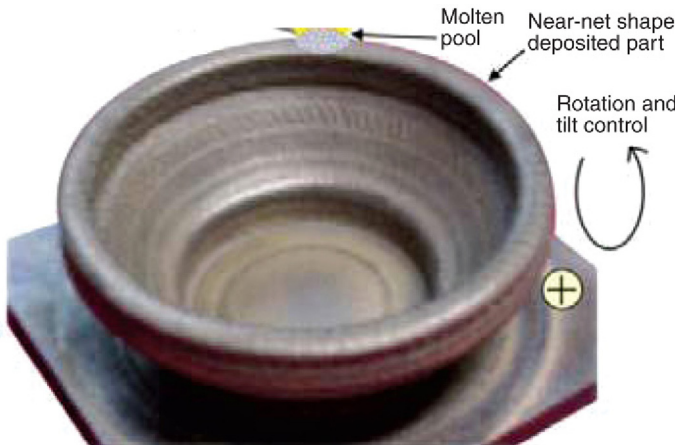


Figure 24.19 Schematic of the MER plasma transferred arc (PTA) additive manufacturing process [38].

to make it a competitive alternative solution. Recent work has demonstrated that titanium AM parts can be successfully produced using much lower cost angular powders [38, 39]. In one program [38], titanium sponge was blended with Al and V powder or Al/V master alloy to produce the Ti-6Al-4V composition. After processing this combination through a plasma transferred arc (Figure 24.19) the as-fabricated tensile properties were at cast and wrought levels: 980 MPa (142 ksi) UTS, 882 MPa (128ksi) YS, and 10% elongation, and S-N fatigue was at ingot metallurgy levels. Later work with ADMA Products TiH₂ powder was equally successful. In another work, angular Metalysis powder [39] was first converted to a spherical morphology and then fabricated by AM. Such an example is a turbocharger for an auto engine shown in Figure 24.20.



Figure 24.20 Automotive component produced from Metalysis powder after spheroidization of the powder [39].

Interestingly, primary work on low-cost titanium AM has targeted the automotive applications, low cost always being a primary concern with the auto industry.

Another major research focus in the AM is dedicated toward process monitoring, control, and in-line inspection. As AM involves layer-by-layer buildup, it allows unique opportunity for in-line inspection of each layer during the build. Various investigations are underway to develop in-line inspection tools for AM processes using ultrasonic, x-ray, and other tools. A combination of latest sensor technologies and predictive control algorithms have shown to be able to compensate for over- or underbuild of a layer caused by issues from toolpath overlap or powder catchment [27, 40]. On-line spectroscopic analysis of meltpool plasma has yielded promises of monitoring and possibly controlling chemistry of build material [27]. Advances in process monitoring and control are being well complemented by mathematical modeling of heat flow and microstructure evolution and predicting mechanical behavior of AM-built titanium [31, 41–42].

With the acceptance of AM in mainstream manufacturing, researchers are focusing on exploiting the added benefits of AM: (1) ability to build a single part with multiple materials or graded materials [43–44] and (2) applying wear-resistant coatings on titanium parts [44–46]. An example is graded coating of Rene 88 on Ti6Al4V [44] and Mo-WC coating on Ti6Al4V material [45] and surface alloying with N, C, or B to form hard coatings of TiN, TiC, or TiB [46]. Building multimaterial components require process and control development as well as developing software capability that will allow building a single object with multiple materials. Another area of research focus is software development for interpretation of the computed tomography/magnetic resonance imaging data, and subsequent translation into CAD data for building customized biomedical products, such as patient-specific implants for the orthopedic industry [47].

24.7 Summary

The past few years have shown significant advances in the AM technologies leading to the production of fully functional parts using titanium and its alloys. While PBF technologies offer the ability to build hollow near-net shapes with finer resolution, directed energy-based technologies offer the ability to add features on existing parts and remanufacture/repair damaged parts, besides building parts directly from CAD data. Most of the studies reveal that the mechanical properties of AM material are as good as or better than the conventionally fabricated titanium alloys. Selection of the right AM technology along with proper design optimization can lead to very significant savings through greatly reduced buy-to-fly ratios, overall weight reduction, scrap reduction, etc. Besides this, these technologies offer design freedom that conventional manufacturing does not. However, full exploitation of the benefits of AM depend largely on educating the manufacturing and design community and successful integration of these technologies in the manufacturing industry. The aerospace and medical industries have so far been the largest driver for the usage of titanium AM materials, while other industries, such as the automotive industry, are beginning to exploit the

benefits of AM of titanium alloys. The recent push in low-cost titanium powders is expected to expand usage of AM in more cost-sensitive industries such as automotive.

Acknowledgments

The authors recognize inputs for this chapter and useful discussions with the following: Jim Sears, Ryan DeHoff, Richard Grylls, Jessica Nehro, Anders Hultman, Scott Thompson, Laura Kinkopf, Michael Cloran, David Whittaker, Karl D' Ambrosio, and Ma Quin.

References

- [1] F.H. (Sam) Froes, Powder metallurgy of titanium alloys, in: Chang Isaac, Zhao Yuyuan (Eds.), *Advances in Powder Metallurgy*, Woodhead Publishing, Philadelphia, USA, 2013, p. 202.
- [2] F.H. (Sam) Froes, Imam M. Ashraf, Fray Derek (Eds.), *Cost Affordable Titanium*, TMS, Warrendale, PA, 2004.
- [3] M.N. Gungor, M.A. Imam, F.H.(Sam) Froes (Eds.), *Innovations in Titanium Technology*, TMS, Warrendale, PA, 2007.
- [4] M.A. Imam, F.H.(Sam) Froes, K.F. Dring (Eds.), *Cost-Affordable Titanium III*, Trans Tech Publications Ltd, Switzerland, 2010.
- [5] M.A. Imam, F.H.(Sam) Froes, R.G. Reddy (Eds.), *Cost Affordable Titanium IV*, Trans Tech Publications, Switzerland, 2013.
- [6] F.H. (Sams) Froes, D. Eylon, H. Bomberger (Eds.), *Titanium Technology: Present Status and Future Trends*, TDA, Dayton, OH, 1985.
- [7] F.H. (Sams) Froes, Y. Te-Lin, H.G. Weidinger Titanium, Zirconium and Hafnium Chapter 8, in: K.H. Matucha (Ed.), *Materials Science and Technology – Structure and Properties of Nonferrous Alloys*, vol. 2, VCH Weinheim, FRG, 1996, p. 401.
- [8] F.H. (Sams) Froes, Titanium, chapters 3.3.5a – 3.3.5e *Encyclopedia of Materials Science and Engineering*, in: P. Bridenbaugh (Ed.), Elsevier, Oxford, UK, 2000.
- [9] F.H. (Sam) Froes (Sam), Titanium Alloys, chapter 8 of the *Handbook of Advanced Materials*, in: Chief J.K. Weasel (Ed.), McGraw-Hill Inc., New York, NY, 2000.
- [10] F.H. (Sam) Froes (Sam) Titanium Metal Alloys, *Handbook of Chemical Industry Economics, Inorganic*, in: Chief Jeff Ellis (Ed.), John Wiley and Sons Inc., New York, NY, 2000.
- [11] R.R. Boyer, G. Welsch, E.W. Collings E W (Eds.), *Materials Properties Handbook: Titanium Alloys*, ASM Int., Materials Park, OH, 1994.
- [12] F.H. (Sam) Froes, Eylon D, Powder metallurgy of titanium alloys, *Int. Mater. Rev.* 35 (1990) 162.
- [13] F.H. (Sam) Froes, C. Suryanarayana, Powder Processing of Titanium Alloys, in: A. Bose, R.M. German, A. Lawley (Eds.), *Reviews in Particulate Materials*, vol. 1, MPIF, Princeton, NJ, 1993, p. 223.
- [14] Defence News, Advanced Manufacturing Shows its Merits, June 10, 2013, p. 24.
- [15] http://www.eos.info/additive_manufacturing/for_technology_interested.
- [16] <http://www.arcam.com/technology/additive-manufacturing/>.
- [17] <http://www.dm3dtech.com/index.php/expertise-innovations/experticeandinnovations-dmddtechnology>.

- [18] <http://www.morristech.com/Docs/Ti64ELI%20DataSheet.pdf>.
- [19] B. Dutta, Private communication, DM3D Technology, July 2013.
- [20] S. Stecker, K.W. Lachenberg, H. Wang, R.C. Salo, Advanced electron beam free form fabrication methods & technology, AWS Conference (2006) 35–46.
- [21] <http://www.optomec.com/Additive-Manufacturing-Technology/Laser-Additive-Manufacturing>.
- [22] <http://resources.renishaw.com/en/details/brochure-the-power-of-additive-manufacturing--57719>.
- [23] http://stage.slm-solutions.com/index.php?slm-500_en.
- [24] <http://www.industriallaser.com.au/pdf/X%20Line%201000R%20Brochure.pdf>.
- [25] R. Dehoff, C. Duty, W. Peter, Y. Yamamoto, W. Chen, C. Blue, C. Tallman, Case study: additive manufacturing of aerospace brackets, *Adv. Mater. Process.* 171 (3) (2013) 19–22.
- [26] E.M. Lawrence, M.G. Sara, M. Edwin, M. Frank, B.W. Ryan B., Next generation orthopaedic implants by additive manufacturing using electron beam melting, *Int. J. Biomater.* 2012, 14 article ID 245727, doi:10.1155/2012/245727.
- [27] B. Dutta, S. Palaniswamy, J. Choi, L.J. Song, J. Mazumder, Additive manufacturing by direct metal deposition, *Adv. Mater. Proc. May* (2011) 33–36.
- [28] B. Dutta, S. Palaniswami, J. Choi, J. Mazumder, Rapid manufacturing and remanufacturing of DoD components using direct metal deposition, *AMMTIAC Quarter.* 6 (2) (2012) 5–9.
- [29] B. Dutta, H. Natu, J. Mazumder, Near net shape repair and remanufacturing of high value components using DMD, *TMS Proceedings of the Fabrication, Materials, Processing and Properties*, vol. 1, 2009, pp. 131–138.
- [30] Titanium Alloy Direct Deposited Products Ti-6Al-4V Annealed, SAE Aerospace Material Specification (AMS) 4999A, Sept 2009, <http://www.sae.org/technical/standards/AMS4999A>.
- [31] F. Wang, S. Williams, P. Colegrove, A.A. Alphonso, Microstructure and mechanical properties of wire and arc additive manufactured Ti-6Al-4V, *Metall. Mater. Trans. A* Sept. (2012) 1–10.
- [32] K. Mari, G. Preston, O. Kelly, L. Guo, E. M. Lawrence, M. G. Sara, M. Edwin, T. Okabe, Evaluation of titanium alloys fabricated using rapid prototyping technologies – electron beam melting and laser beam melting, *Materials* 4 (2011) 1776–1792.
- [33] ASM Handbook, vol. 2, Properties and Selection: Nonferrous Alloys and Special Purpose Materials, pp. 621, 637.
- [34] R. K. Hermann, O. Sven, Nowotny, Steffen, Laser cladding of the titanium alloy Ti6242 to restore damaged blades, *Proceedings of the 23rd International Congress on Applications of Lasers and Electro-Optics*, 2004 pp. 1–10.
- [35] A. Eleonora, A. Salmi, Economics of additive manufacturing for end-useable metal parts, *Int. J. Adv. Manuf. Technol.* 62 (2012) 1147–1155.
- [36] http://www.manufacturingthefuture.co.uk/_resources/case-studies/TSB-AirlineBuckle.pdf.
- [37] M. Quin, Private communication, July 2013.
- [38] J.C. Withers, V. Shapovalov, R. Storm, R.O. Loutfy, There is Low Cost Titanium Componentry Today, Reference #5, p. 11.
- [39] P. Whittaker, posted on <http://www.ipmd.net/news/002519.html>, MetalYSIS' Titanium Powder used to 3D print Automotive Parts.
- [40] L. Song, V. B. Singh, B. Dutta, J. Mazumder, Control of melt pool temperature and deposition height during direct metal deposition process, *Int. J. Adv. Manuf. Technol.* May (2011) 10.1007/s00170-011-3395-2.
- [41] K. Makiewicz, S.S. Babu, M. Keller, A. Chaudhary, Microstructure evolution during laser additive manufacturing of Ti-6Al-4V alloy, *Trends in Welding Research 2012 Proceedings of the 9th International Conference (ASM International)*, February 01, 2013, pp. 970–977.

- [42] S.M. Kelly, S.L. Kampe, Microstructural evolution in laser-deposited multilayer Ti-6Al-4V builds: Part II. Thermal Modelling, *Metall., Mater. Trans. A* 35A (2004) 1869–1879.
- [43] P.C. Collins, R. Banerjee, S. Banerjee, H.L. Fraser, Laser deposition of compositionally graded titanium/vanadium and titanium/molybdenum alloys, *Mat. Sci. Eng. A* 352 (2003) 118–128.
- [44] X. Lin, T.M. Yue, H.O. Yang, W.D. Huang, Solidification behavior and the evolution of phase in laser rapid forming of graded Ti6Al4V-Rene88DT alloy, *Metall. Trans. A* 38A 2007, 127–137.
- [45] W. Pang, H.C. Man, T.M. Yue, Laser surface coating of Mo–WC metal matrix composite on Ti6Al4V alloy, *Mat. Sci. Eng. A* 390 (2005), 144–153.
- [46] R. Filip, Alloying of surface layer of the Ti-6Al-4V titanium alloy through the laser treatment, *JAMME*, 15(1–2) (2006) 174–180.
- [47] L.B. Bourell, C.L. Leu, W.D. Rosen, Roadmap for additive manufacturing identifying the future of freeform processing, The University of Texas at Austin, Laboratory for Freeform Fabrication, Advanced Manufacturing Center, 2009.