Chapter 2
Additive Manufacturing Metal, the Art of the Possible

Abstract Novel applications and designs showcase the power and potential of 3D printing and additive manufacturing of metal. This chapter identifies the market segments where AM is making inroads and having the greatest impact. The momentum in advances of AM metal technology, historically driven by rapid prototyping for engineering applications, is rapidly changing and moving toward the production of high value components made of advanced materials. Application examples include critical products such as those certified for use in aerospace and for medical hardware. In addition, customized artistic designs and one of a kind personalized items are being created on demand. Unique designs and functions are being incorporated into parts unthought-of only yesterday. The potential to transform industry and realize significant cost and energy savings is demonstrated by the use complex cooling channels in hardware for the tool and die industry to high-performance heat exchangers and wear resistant coatings in the energy, oil and gas industries. Repair and remanufacturing of components with every increasing complexity using multiple and advanced materials is being demonstrated. This chapter provides examples of components and products within the hottest segments of AM metal technology, introducing the art of the possible.

2.1 AM Destinations: Novel Applications and Designs

So, where we are today? What is the state of development and application of AM technology as applied to metals? What is unique to these applications that make them attractive to using AM? (Fig. 2.1) While the best of the technology is most likely under wraps in the back shop of a corporate research lab or cutting-edge fabrication shop, there are a number of applications we would like to showcase. Some of these examples are technology demonstrations, forward looking marketing

J.O. Milewski, *Additive Manufacturing of Metals*, Springer Series in Materials Science 258, DOI 10.1007/978-3-319-58205-4_2

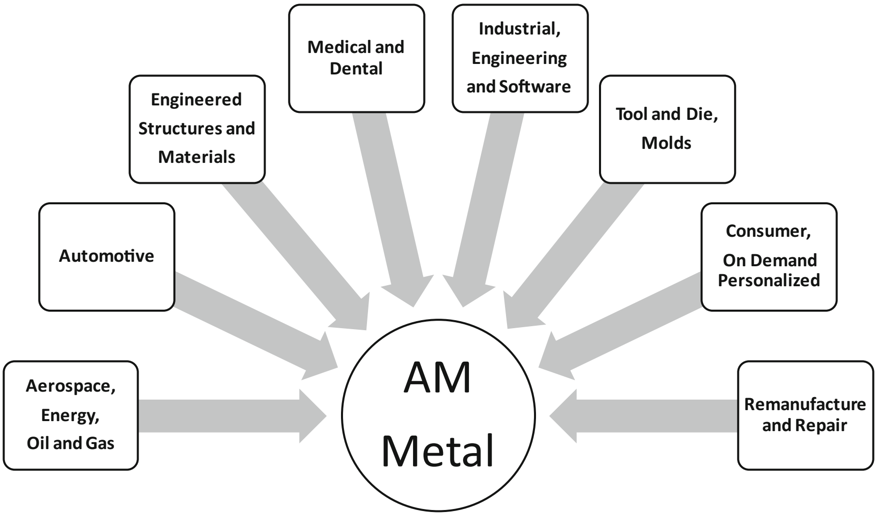

Fig. 2.1 Applications of AM metal

examples, or honest to goodness functional prototypes, but they all serve the purpose of pushing pins and drawing circles on the AM roadmap.

A number of examples of out of the box thinking and novel designs are provided as vectors for inspiration or perhaps outright destinations. What is a killer application and how does one get there? Truly unique applications are emerging every day. Some are destined to become product lines and quiet money makers, others may serve as mental launch pads for inventions and a method beyond today's thinking.

Figure 2.2 is perhaps the most widely publicized AM part, the GE Aero LEAP fuel nozzle, featuring a cobalt chrome alloy and other materials. It combines 18 components into one part with complex passageways and cutting-edge design offering higher durability and efficiency. With 19 nozzles per engine and a future production rate of 1700 engines per year, GE Aviation has set the goal of 32,000 nozzles per year when in full production, 100,000 parts by 2020. GE has invested $3.5 billion dollar in new plants to produce these nozzles. These nozzles are already in flight testing.

In another example General Electric has completed testing its Advanced Turboprop (ATP) technology demonstration engine which will power the all-new Cessna Denali single-engine aircraft. The engine is 35%-additive manufactured

Fig. 2.2 General Electric LEAP nozzle[1]

featuring a *clean sheet* design used to validate additive parts, reduce the weight by 5% while contributing a 1% improvement in specific fuel consumption (SFC).[2] In another additive test program, the CT7-2E1 demonstrator engine was designed, built and tested in 18 months, reducing more than 900 subtractive manufactured parts to 16 additive manufactured parts.

2.2 Artistic

Artistic applications of 3D metal printing are leading the way toward exploration of entirely new designs, shapes and processes. Some of these capture the essence of freeform, emotional design. A design and part by Bathshiba Sculpture LLC[3] is one example, shown in Fig. 2.3.

[1]Courtesy of GE Aviation, reproduced with permission.

[2]GE Aviation press release, October 31, 2016, GE tests additive manufactured demonstrator engine for Advanced Turboprop, http://www.geaviation.com/press/business_general/bus_20161031a.html, (accessed January 20, 2017).

[3]Bathshiba Sculpture LLC Web site, http://bathsheba.com/, (accessed April 6, 2015).

Fig. 2.3 3D printed metal sculpture[4]

As software and material become cheaper, artistic access to solid free form design tools will allow a further expansion into the world of emotional design. As music, color, video, and other forms of dynamic audio and visual 2D art can evoke emotional response or inspirational experience, so will 3D virtual reality (VR) headsets and the 3D VR experience. Capturing moments of 3D VR and bringing them back to the physical world will be enabled by AM. This will include kinetic artwork and parts that change in time within the local environment of use.

3D printing machines designed for precious metals[5] feature a powder management process developed for the jeweler and watchmaking industries, ensuring full accountability of the valuable powders and providing quick metal changeover through a cartridge-based system. The 3D metal printing machines used to create jewelry can be smaller and relatively less expensive than machines used to print automotive and aerospace parts. Artwork and jewelry does not require the same levels of certification and control needed by aerospace, automotive and medical devices, therefore making jewelry an attractive market for additive processing. Artistic designs that cannot be produced in metal by any other method are made possible while using less material and streamlining the production of custom made-to-order pieces. Hollow structures with internal supports allow the fabrication of larger pieces with the desired strength but without the weight or cost or a solid piece. AM systems such as shown in Fig. 2.4a feature small build volumes ideal for the rapid fabrication of small pieces such as jewelry while minimizing the total volume of precious metal powder stock. They use a small laser focal spot sizes, providing excellent detailed resolution, allowing the creation of fine features and structures, as shown in Fig. 2.4b and c.

[4]Courtesy of Bathsheba Grossman, reproduced with permission.

[5]Cooksongold website, http://www.cooksongold-emanufacturing.com/products-precious-m080.php, (accessed August 13, 2015).

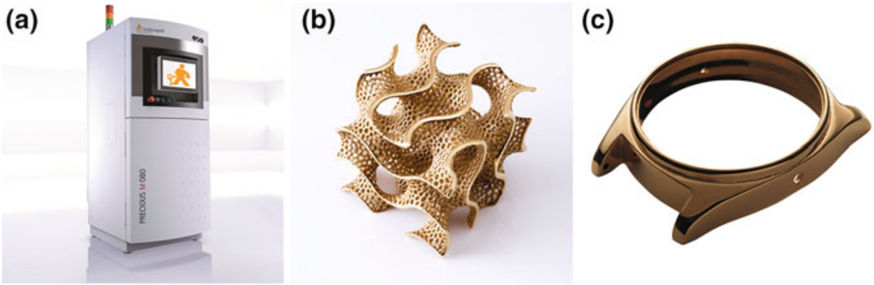

Fig. 2.4 **a** Direct Metal Laser Sintering machine for jewelry. "M 080 Direct Precious Metal 3D Printing System,"[6] **b** Sculptural design printed in gold.[7] **c** 3D printed gold watchcase.[8]

2.3 Personalized

Renishaw and Empire Cycle teamed up to build the first design of the titanium bicycle as described in an article from Engineering and Technology magazine, "First 3D printed bike enters record books," by Alex Kalinauckas.[9] Figure 2.5 shows the frame components as-fabricated in sections within the AM machine build volume. Figure 2.6 shows the assembled frame with wheels and additional bicycle components. Technology demonstrations such as this highlight the ability to produce personalized designs out of specialty and lightweight materials such as titanium. Complex shapes with lightweight internal strengthening structures and flowing organic forms allow the combination of engineering and artistic features to produce unique one of a kind individualized objects.

3D scanning and printing is now commonly used in the fabrication of custom-fit hearing aids and other such personal devices. Although currently made in polymers, the hearing aid example shows the potential for 3D scanning and printing to disrupt market places and radically change products made specifically for you. Mass produced items have the appeal of low cost but in some cases the benefit of a customized item made specifically for you will offer the greatest value. As scanning and digital definition of our bodies becomes common place, every human-to-object interface

[6]Courtesy of Cooksongold and EOS, reproduced with permission.

[7]Manufactured and designed by Cooksongold, reproduced with permission.

[8]Manufactured by Cooksongold, designed by Bathsheba Grossman, reproduced with permission

[9]Article from Engineering and Technology magazine, "First 3D printed bike enters record books", March 18, 2015, by Alex Kalinauckas, http://eandt.theiet.org/news/2015/mar/3d-bikeframe.cfm, (accessed March 26, 2015).

Fig. 2.5 Titanium bike frame as-built using AM[10]

Fig. 2.6 Titanium bike frame as assembled[11]

holds the potential for customization. As an example, a mobile app[12] may be used to order a personalized piece of jewelry. Personalized rings with the initials of a loved one, can be printed in various precious metals as shown in Fig. 2.7. Custom made and personalized items, such as golf club heads,[13] are being produced by Ping. Although out of the price range for many, these types of items can infer personal taste and passion for the sport, as well as status, for all-out equipment freaks (Fig. 2.8). Any sport, personal item or household fixture with a high end market can be a target of innovative and unique designs made possible using AM metal.

[10]Courtesy of Renishaw, reproduced with permission.

[11]Courtesy of Renishaw, reproduced with permission.

[12]Love by me website and app, http://love.by.me/, (accessed August 13, 2015).

[13]3D article, http://3dprint.com/46036/golf-equipment-manufacturer-ping-introduces-golfs-first-3d-printed-putter/, (accessed August 13, 2015).

Fig. 2.7 Personalized jewelry[14]

Fig. 2.8 Custom golf club head[15]

2.4 Medical

“Disruptive” applications for AM are beginning to emerge into the manufacturing mainstream. One such application is that of dental devices, where small custom-fit crowns and dental implants are disrupting the historic methods for the fabrication of these components. Figure 2.9 shows dental crowns and bridges produced by direct

[14]Courtesy of Skimlab and Jweel, reproduced with permission.

[15]Courtesy of Ping, reproduced with permission.

Fig. 2.9 Additively manufacturing dental hardware[17]

metal laser sintering (DMLS). In one example[16] an EOS M 100 DMLS machine fuses Cobalt Chrome SP2 alloy, a medical material using a certified and qualified process. Small lot size, high precision and high value products such as these are seeing wide adoption.

Another application soon to be widely realized is metal medical implants, as certifications for medical use are being approved for human use in the European Union (EU) and US. Over 50,000 medical devices have been implanted for the medical industry as produced by the electron beam melting (EBM) additive manufacturing process alone.[18] The benefits provided by AM are those of rapid production of personalized fit items for direct use, such as for implants, or secondary uses, such as drill guides and fixtures using the patient's own medical imaging to create 3D models anatomically matched devices. The accuracy of direct AM parts is sufficient for these applications, while the surface finish or porous structures offer advantages for bone ingrowth. These complex engineered surfaces are cleaned and sterilized offering a biological fixation intended to replace cemented fixation to optimize the implant–host interface. Figure 2.10 shows a 3D printed titanium cranial implant on a 3D printed skull model.

In another example, Stryker has received 510(k) clearance from the U.S. Food and Drug Administration today for its *Tritanium* PL Posterior Lumbar Cage, spinal

[16]EOS application for dental crowns, http://www.eos.info/eos_at_ids_additive-manufacturing, (accessed August 13, 2015).

[17]Courtesy of EOS, reproduced with permission.

[18]Arcam White Paper, Optimizing EBM Alloy 718 Material for Aerospace Components, Francisco Medina, Brian Baughman, Don Godfrey, Nanu Menon, downloaded from, http://www.arcam.com/company/resources/white-papers/, (accessed January 20, 2017).

Fig. 2.10 Titanium skull implant[19]

implant device for patients with degenerative disk disease.[20] The device is manufactured via a 3D additive manufacturing process using their proprietary Tritanium technology, a novel highly porous titanium material designed for bone ingrowth and biologic fixation.

The FDA[21] Website for Medical Application of 3D printing provides additional information as well as links to draft guidance on the Technical Considerations for Additive Manufactured Devices to obtain public feedback. When finalized and in effect, the guidance will advise manufacturers who are developing and producing devices through 3D printing techniques with recommendations for device design, manufacturing, and testing.

Materials offering sufficient strength and biocompatibility are those currently used in medical devices, such as cobalt chrome and titanium alloys, which are easily fabricated using AM. Specialty metals such as tantalum may also see wider use in AM produced devices or AM deposited surfaces. Such medical devices command a high price and fit well within the build volume of powder bed fusion processes.

[19]Courtesy of 3T RPD, reproduced with permission.

[20]Stryker press release, http://www.stryker.com/en-us/corporate/AboutUs/Newsroom/ProductBulletins/169618, (accessed January 20, 2017).

[21]FDA Web site, Medical Applications of 3D Printing, http://www.fda.gov/MedicalDevices/ProductsandMedicalProcedures/3DPrintingofMedicalDevices/ucm500539.htm, (accessed January 20, 2017).

Fig. 2.11 Titanium propulsion tank[23]

2.5 Aerospace

Lockheed Martin and Sciaky have demonstrated the use of AM for the creation of a titanium propulsion tanks using EBAM, as shown in Fig. 2.11. In this case, the EBAM process is used to create a rough blank shape that can later be machined into a shape that would otherwise need to be formed by obtaining commercially available titanium plate, pressing into shape, then machining. Pressing would require a forming punch and die and a large hydraulic press. Vessels of various sizes would require a costly punch and die for each shape.[22]

[22]Sciaky press release detailing the example in Fig. 2.11, http://www.sciaky.com/news_and_events.html, (accessed March 26, 2015).

[23]Courtesy of Lockheed Martin, reproduced with permission.

Figure 2.12 show a full-scale rocket engine part 3D printed out of copper by NASA.[24] The additively manufactured part is designed to operate at extreme temperatures and pressures and demonstrates one of the advanced technologies NASA is evaluating for use in fabricating parts for the mission to the planet Mars. In another application, Aerojet Rocketdyne has fabricated and demonstrated the hot-fire testing of a rocket engine thrust chamber made using AM deposition of a copper alloy.[25] Figure 2.13 shows a liquid oxygen/gaseous hydrogen rocket injector assembly, built using additive manufacturing technology, being hot-fire tested at NASA Glenn Research Center. The potential reduction in fabrication lead times and costs provides strong motivation for evaluating the AM technology. Space and aerospace applications require strict procedures and certification for processes and components. Significant saving may be realized in the reduction of the number of certified parts and processes, such as joining, used to produce a component. The reduction in weight can result in significant savings during the launch into space escaping the gravity well of earth or fuel saving during commercial aircraft flights. The reduction in material waste during fabrication of expensive specialty materials such as nickel-based alloys or titanium is also an important factor in justifying the use of additive manufacturing. A panel at the "Technology Development and Trends in Propulsion and Energy", 2015 AIAA Propulsion and Energy Forum[26] describes the benefit of designing hardware with complex shapes and features not possible using conventional methods. Additional benefits in system efficiency and environmental factors such as noise and emissions may also be realized.

In a business case study, the Airbus Group EADS Innovations performed an eco-assessment analysis as applied to a standard Airbus A320 nacelle hinge bracket, shown in Fig. 2.14 and strove to include detailed aspects of the overall lifecycle: from the supplier of the raw powder metal, to the equipment manufacturer EOS, to the end-user, Airbus Group Innovations. An entire lifetime assessment contrasted costs and savings of each method along the entire manufacturing chain from cradle

[24]NASA 3D Prints the World's First Full-Scale Copper Rocket Engine Part, Tracy McMahan, April 21, 2015, http://www.nasa.gov/marshall/news/nasa-3-D-prints-first-full-scale-copper-rocket-engine-part.html, (accessed May 15, 2016).

[25]NASA and Aerojet Rocketdyne Successfully Tests Thrust Chamber Assembly Using Copper Alloy Additive Manufacturing Technology using copper alloy additive manufacturing technology, http://globenewswire.com/news-release/2015/03/16/715514/10124872/en/Aerojet-Rocketdyne-Hot-Fire-Tests-Additive-Manufactured-Components-for-the-AR1-Engine-to-Maintain-2019-Delivery.html#sthash.UU5Yuc9e.dpuf, (accessed May 14, 2016).

[26]"Technology Development and Trends in Propulsion and Energy," a panel at the 2015 AIAA Propulsion and Energy Forum. http://www.aiaa-propulsionenergy.org/Notebook.aspx?id=29179, (accessed August 13, 2015).

Fig. 2.12 Copper rocket nozzle[27]

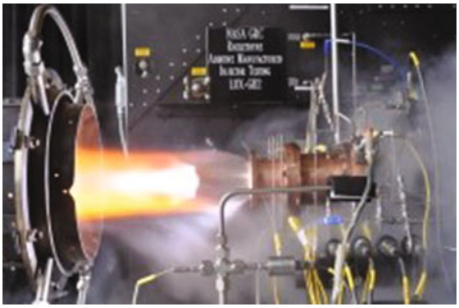

Fig. 2.13 Testing of an additive manufactured rocket nozzle[28]

to grave, indicating a lifetime cost saving primarily due to reduced weight (titanium versus steel, lightweight design). Future comparisons with a wider scope of options, such as epoxy composites, to determine the cost of environmental effects will shed additional light on potential costs or benefits of all AM/SM options.

[27]Courtesy of NASA.

[28]Courtesy of NASA Glenn Research Center.

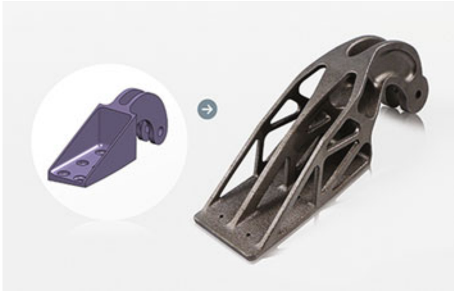

Fig. 2.14 A design for Additive Manufacturing meeting lightweight targets[29]

EOS and Airbus Group Innovations Team[30] (now the EADS Innovation Works) cites another study associated with the weight reduction benefits of AM designs with respect to energy consumption and the reduction of CO_2 emissions by nearly 40% over the full lifecycle of a conventionally cast steel aircraft bracket in comparison to an additive manufactured direct metal laser sintered titanium bracket with optimized topology. A savings of 25% in the reduction of titanium scrap and a possible weight savings of 10 kg per aircraft was also cited.

2.6 Automotive

Formula 1 race car design teams are benefitting from the design freedom and rapid prototype/testing to speed fabrication cycles to gain competitive advantage off the track. In these cases, cost is a secondary consideration while weight reduction and design freedom are paramount. These sorts of critical application components, made of plastics, metals, or composites are not subject to the same testing and certification constraints as commercial man-rated components, thus providing a high-performance test bed for these components. As they say, racing improves the breed and this applies to the materials, designs, methods, and machines here as well. Such applications provide a proving ground for AM technologies, although the success stories and detailed methods will be tightly held as company confidential information. A steering knuckle part for a race car fabricated by DMLS is shown in Fig. 2.15. Two additional examples include a light twin-walled drive shaft and

[29]Courtesy of Airbus Group Innovations and EOS, reproduced with permission.

[30]Press release, February 14, 2014, EOS and Airbus Group Innovations Team on Aerospace Sustainability Study for Industrial 3D Printing, http://www.eos.info/eos_airbusgroupinnovationteam_aerospace_sustainability_study, (accessed May 14, 2016).

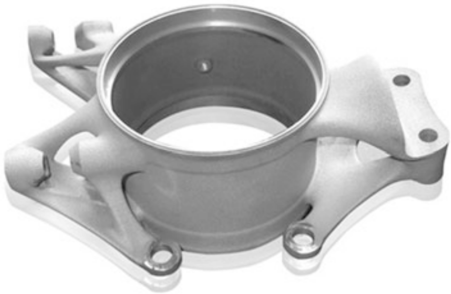

Fig. 2.15 Race car steering knuckle produced by DMLS[31]

Fig. 2.16 AM produced automotive piston[32]

brake disks that are 25% lighter, with better cooling. Figure 2.16 shows an AM printed piston for automotive application. While the big attraction of AM metal processing of automotive parts remains rapid prototyping of functional test parts, the production of specialty and hard to find parts, such as those used in vintage automotive restoration is actively being pursued. Mass production of automotive parts is out of reach of current direct metal AM processes but AM methods starting with a CAD model and resulting in a metal part such as by producing a sand mold or plastic pattern is gaining wider acceptance.

Casting of large complex components can be realized by directly 3D printing a sand mold and then casting a part in metal can save development time, allowing for

[31]Courtesy of EOS and Rennteam Uni Stuttgart (www.rennteam-stuttgart.de), reproduced with permission.

[32]Courtesy of Beam IT, reproduced with permission.

Fig. 2.17 BinderJet produced silica sand mold for casting an aluminum Formula 1 transmission housing[34]

multiple design iterations during the prototyping cycle. Figure 2.17 shows a silica sand casting mold used to cast a Formula 1 race car transmission housing using aluminum alloy A356. ExOne provides a case study[33] where a batch size of five castings were produced at the cost of 1500 € per part compared a lot cost of 15,000 €–20,000 € using conventional patterns, tools and lost foam casting methods. This demonstrates that 3D printing technology can make sense for certain small lot size casting applications.

2.7 Industrial Applications Molds and Tooling

Mold inserts can benefit from complex conformal cooling channels to speed the molding process and improve part quality. Figure 2.18 provides a view of a model part revealing complex cooling channels made possible by 3D printing (right view) and the outer surface of the part produced by the DMLS process in a finished and

[33]ExOne case study, http://www.exone.com/Portals/0/ResourceCenter/CaseStudies/X1_CaseStudies_All%206.pdf, (accessed August 13, 2015).

[34]Courtesy of EXONE, reproduced with permission.

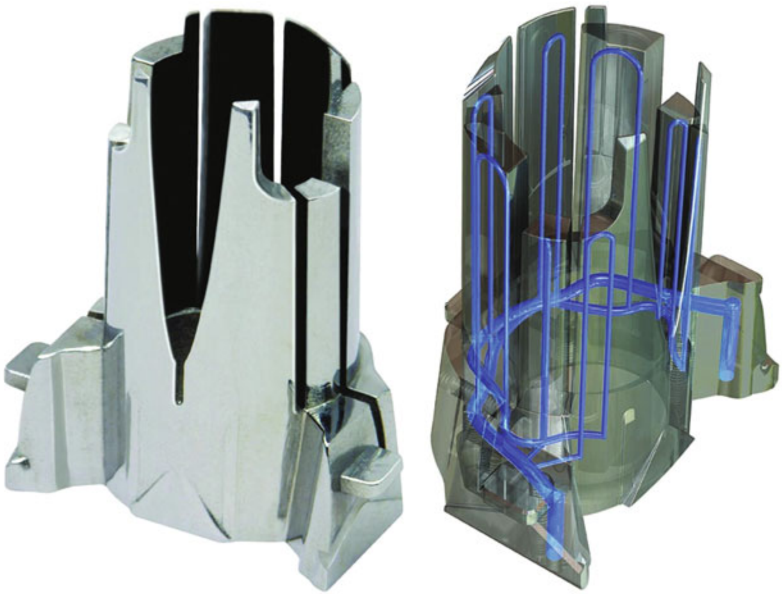

Fig. 2.18 DMLS fabricated part and model showing internal conformal cooling channels[35]

polished condition (left view). Figure 2.19 taken from a case study by GPI Prototype & Mfg. Services of the actual part, shows it was still in use after 190,000 shots resulting in a productivity increase of 48%. Applications such as these place an additional reliance on the computer-aided engineering analysis of potential designs to fully optimize the benefit of AM processing. In addition to conformal cooling, AM metal processing may be used to repair or modify existing tooling to extend the life or increase the performance of existing parts.

2.8 Remanufacture and Repair

Maintenance, repair or overhaul applications can benefit from direct energy deposition to apply coating for original parts or for repair. One such example is explained in an article "Component and Tool Life Extension Using Direct Metal

[35]Courtesy of GPI Prototype & Mfg Services—Lake Bluff, IL, reproduced with permission.

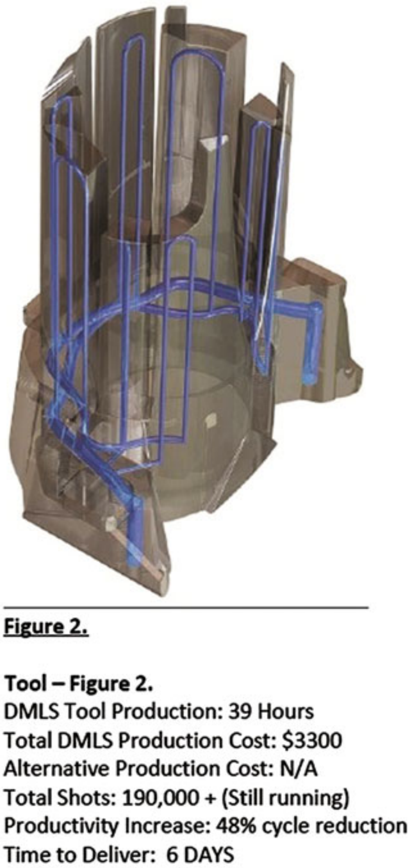

Fig. 2.19 Case study of the actual part in service[36]

Deposition (DMD)",[37] by Dr. Bhaskar Dutta, DM3D Technology, August 20, 2013.

Figure 2.20 shows such an example where a forging tool for a connecting rod has been coated using the DMD process, also known as directed energy deposition (DED). To overcome the heat checking and wear damages during forging, the tool was built using low-cost steel and a high-temperature Co-based alloy was applied in the heat checking areas. In contrast to the mechanical bonding of the chemical

[36]Courtesy of GPI Prototype & Mfg Services—Lake Bluff, IL, reproduced with permission.

[37]MTadditive.com web site "Component and Tool Life Extension Using Direct Metal Deposition (DMD), by: Dr. Bhaskar Dutta, DM3D Technology, August 20, 2013, http://www.mtadditive.com/index.cfm/trends-in-additive/component-and-tool-life-extension-using-direct-metal-deposition-dmd/, (accessed April 6, 2015).

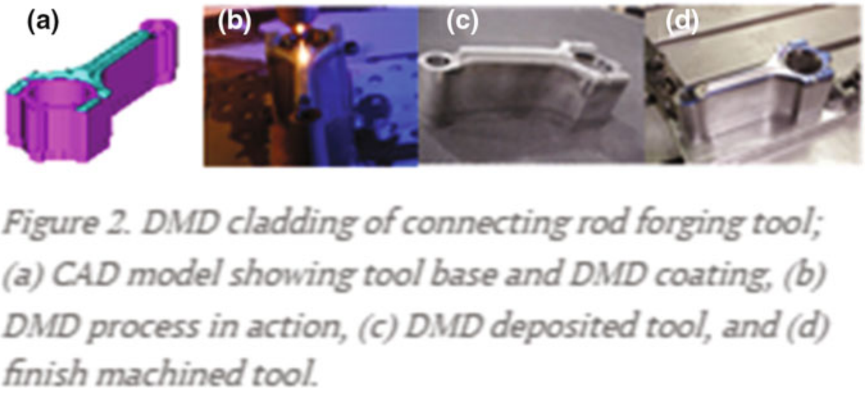

Fig. 2.20 Case study by DM3D Technology of a forging tool modified with cobalt based alloy coating using the DMD process[39]

vapor deposition (CVD) and physical vapor deposition (PVD) and thermal spray coatings, DMD material is bonded to the base steel and can withstand the thermal and fatigue loading of the forging process without chipping of the coating material. DMD built hard facing material was about 6 mm thick to sustain severe forging pressure and also allow for machining of the tool multiple times. DMD applied tools had four times longer life over conventional tooling and resulted in significant cost savings while reducing downtime. In another example[38] Optomec demonstrates repairing an impeller blade using laser beam directed energy deposition (Fig. 2.21).

2.9 Scanning and Reverse Engineering

Scanning technology can use laser or photographs to capture an object's shape and use reverse engineering software to recreate a model of the object. That model can be used to 3D print plastic patterns or sand molds of direct to metal parts.

[38]Impeller repair article, the fabricator, http://www.thefabricator.com/article/metalsmaterials/fabricating-the-future-layer-by-layer, (accessed August 13, 2015).

[39]Courtesy of MTAdditive and DM3D Technology, reproduced with permission.

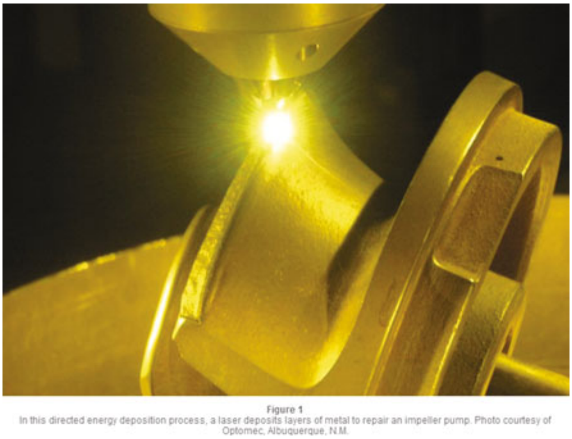

Fig. 2.21 Directed Energy Deposition Repair of Impeller Pump[40]

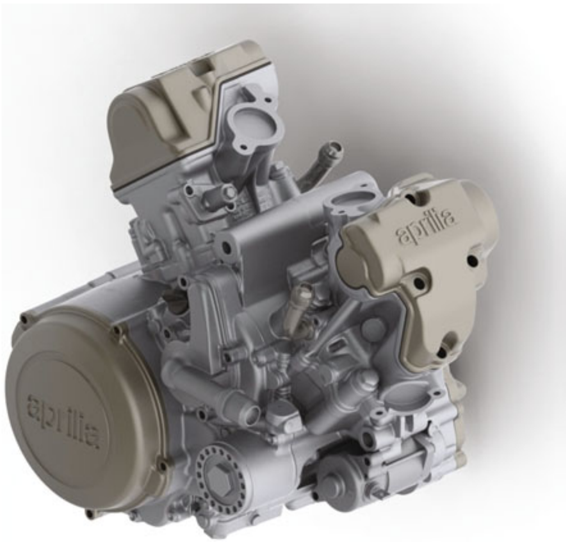

Fig. 2.22 Example of scanned parts to CAD model[43]

Geomagic,[41] owned by 3D Systems, provides hardware and software solutions to allow 3D scanning and the creation of 3D models to be used in original and reverse engineering applications.[42] One example, in Fig. 2.22, demonstrates the ability to

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[40]Photo courtesy of Optomec (reproduced with permission); LENS is a trademark of Sandia National Labs.

[41]Geomagic Web site, http://www.geomagic.com/en/, (accessed March 26, 2015).

[42]Geomagic case study, http://www.geomagic.com/en/community/case-studies/rebuilding-a-classic-car-with-3d-scanning-and-reverse-engineerin/, (accessed March 26, 2015).

[43]Courtesy of 3D Systems, reproduced with permission.

Fig. 2.23 Complex heat exchanger design printed in copper[46]

scan motorcycle engine parts, process the point cloud data into a model that can be features and assembled into a 3D model that can also be used to 3D print a plastic or metal component. The software can interface with professional level computer-aided design (CAD) software such as Catia, Solidworks, etc.

2.10 Software

Software used to create complex designs is being created by cutting-edge companies such as the company WithinLab (now Autodesk Within). The software is used to assist in the design process for complex internal structures, repeating structures, variable density structures, and complex shapes, as needed, helping to realize the potential of AM designs, such as the complex heat exchanger design built in copper as shown in Fig. 2.23. Siavash Mahdavi of Within has a TED talk[44] and the Web site[45] provide videos that explain the technology that can create and optimize latticed microstructures and surface structures. The software adds an extra layer of file encryption enhancing the security of intellectual property.

[44]Siavash Mahdavi TED talk, posted March 13, 2012, http://tedxtalks.ted.com/video/TEDxSalzburg-Siavash-Mahdavi-St;Featured-Talks, (accessed April 6, 2015).

[45]Within Web site with videos and software for medical implant design, http://withinlab.com/overview/, (accessed April 6, 2015).

[46]Courtesy of 3T RPD, reproduced with permission.

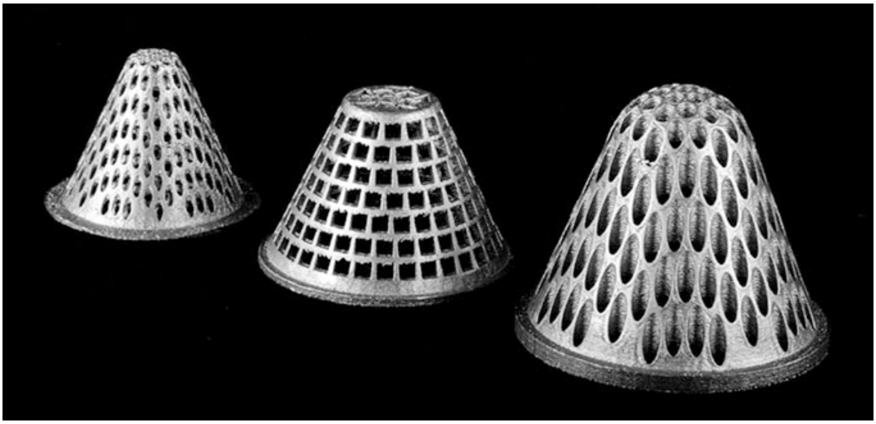

Fig. 2.24 Complex filter designs produced by AM[49]

2.11 Engineered Structures

Complex internal features, such as turbulators to increase heat conduction in cooling channels, combined with conformal cooling channels in molds and mold inserts, allow designers unprecedented freedom in optimizing the thermal or mechanical functions of a part while offering shorter cycle times. Air ducts with laminar flow design, complex heat exchangers with repeated sub-elements and other complex structures, are being demonstrated. The benefits of complex internal structures may outweigh the need for accuracy or surface finish of these structures. One interesting application is associated with filtration technology[47] as shown in Fig. 2.24. AM metal technology was used to create complex filter components offering high flow rates and greater efficiency reducing operating costs. In another example, engineered surfaces at the microscale can improve coating adhesion of interfaces between AM produced titanium hardware and carbon fiber structural members. Figure 2.25 shows a cut away view of the complex internal structure of a gas emissions rake displaying what is made possible by using AM design and fabrication. New applications and complex shapes are being reported every day in a growing number of new industry publications, such as Metal Additive Manufacturing,[48] demonstrating the expanding capability of the technology and those who use it.

[47] Additive Manufacturing-What you need to know, Filtration + Separation.com article, February 20, 2014 article, http://www.filtsep.com/view/37036/additive-manufacturing-what-you-need-to-know/, (accessed March 28, 2015).

[48] Metal Additive Manufacturing, Spring, 2015, Vol. 1, No. 1.

[49] Courtesy of Croft Additive Manufacturing, reproduced with permission.

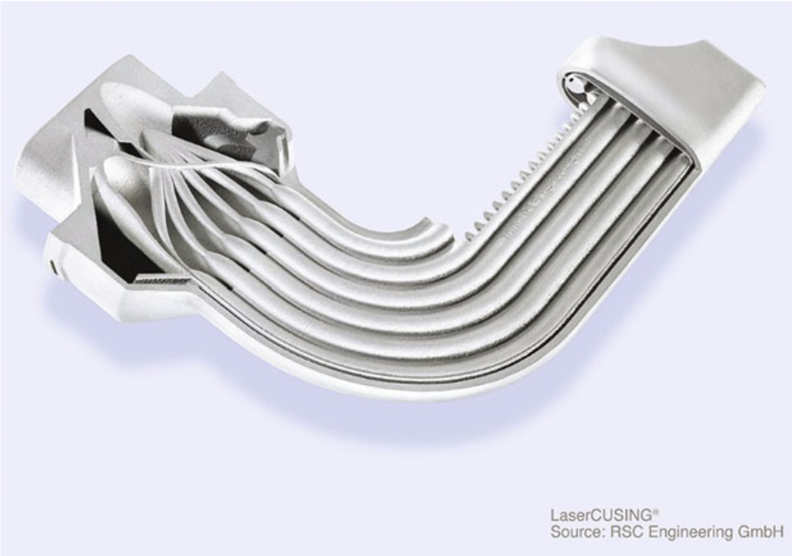

Fig. 2.25 Cut-away view of a gas emissions rake with complex internal structure fabricated using LaserCUSING®[50]

2.12 Functionally Graded Structures and Intermetallic Materials

Ongoing research at universities and government research laboratories demonstrate the ability of AM metal processing to locally affect and potentially control the microstructure of AM deposited metal using the wide range processing parameter available to AM. Electron beam additive manufacturing has been demonstrated to enable site-specific control over the microstructure within an AM metal deposit[51] offering the potential for engineering the metal properties of localized regions and features of a part. The metallurgy and processing science of metal additive manufacturing is an active area of study.[52] An in-depth understanding of the AM metal

[50]Courtesy of Concept Laser GmbH, RSC Engineering GmbH, reproduced with permission.

[51]R.R. Dehoff, M.M. Kirka, W.J. Sames, H. Bilheux, A.S. Tremsin, L.E. Lowe and S.S. Babu: ‘Site specific control of crystallographic grain orientation through electron beam additive manufacturing’, Mater. Sci. Technol., 2015, 31, (8), 931–938.

[52]W.J. Sames, F.A. List, S. Pannala, R.R. Dehoff & S.S. Babu (2016): The metallurgy and processing science of metal additive manufacturing, International Materials Reviews, http://dx.doi.org/10.1080/09506608.2015.1116649, (accessed May 14, 2016).

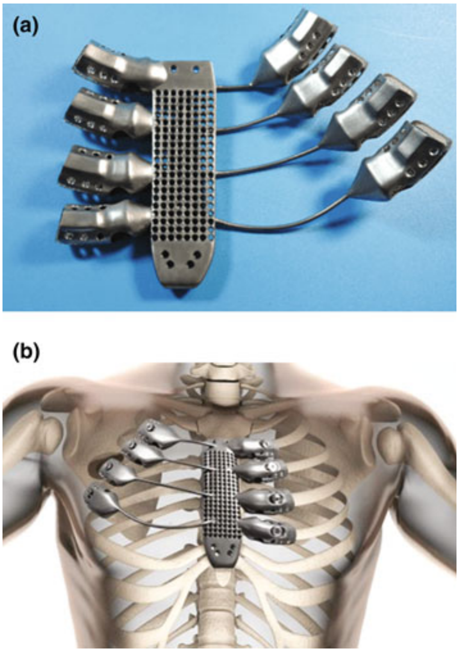

Fig. 2.26 **a** Custom sternum chest implant.[53] **b** Sternum chest implant illustration.[54]

processes, the chemistry and metallurgy resulting from these processes, combined with a first principal understanding of the metallurgy and physics may offer simulation tools for the prediction and design and for controlling and engineering the resulting properties and performance of AM produced parts. While localized control of the micro structure within an AM produced part is still at the research stage, localized control of the structure of the deposit at very small scales is made possible by AM and can be used to functionally grade the materials such as by adding a coating or additional layers of a different material. Grading or changing the structure of the deposit, such as within medical implants, can locally change the part function from that of a load bearing member to a region that fosters bone ingrowth. Figure 2.26a and b shows a titanium prosthetic sternum or rib cage fabricated using the PBF-EB process. It was implanted into the chest of a 54-year old cancer patient who lost his sternum and four ribs with the removal of a large tumor. Engineers at Anatomics in Melbourne, Australia used the patient's own CT scans to engineer the custom shaped device. The perforated sternum portion provides rigid strength while the four thin rods are designed to flex during breathing.

[53]Designed by Anatomics Pty Ltd., Melbourne Australia, reproduced with permission.

[54]Designed by Anatomics Pty Ltd., Melbourne Australia, reproduced with permission

Fig. 2.27 Tool insert with internal cooling structures made from Hovadur K220 by SLM.[57]

A cutting-edge example of using a DED laser based system has been demonstrated by Peter Dillon at the Jet Propulsion Laboratory (JPL), using materials such as A286, 304L, Invar36 clad, in a collaboration with Penn State University (PSU), NASA, JPL, and Cal Tech Pasadena. GE Aviation's Avio Aero is working to use TiAl, an intermetallic material offering unique properties and performance, in turbine blades and JPL for functionally graded piping using the EBM electron beam melting process.[55]

2.13 Technology Demonstration

A research team at Fraunhofer ILT in Aachen has demonstrated the use of SLM for the deposition of copper tooling inserts with internal cooling channels,[56] Fig. 2.27. In the InnoSurface project, funded by the German Federal Ministry of Economics and Technology, the team has succeeded in modifying the SLM process by

[55]Metal Additive Manufacturing article, August 20, 2014, http://www.metal-am.com/news/002896.html, (accessed March 26, 2015).

[56]Prototype Today article, http://www.prototypetoday.com/fraunhofer/components-made-from-copper-powder-open-up-new-opportunities, (accessed March 28, 2015).

[57]©Fraunhofer ILT, Aachen/Germany, reproduced with permission

Fig. 2.28 The Solid Concepts 3D printed 1911 pistol[59]

increasing the power from 200 to 1000 W and tailoring the laser beam profile, changing the inert gas control system and mechanical equipment to accommodate the high reflectivity and thermal conductivity of copper to improve laser coupling and melting. A deposit density of near 100% was reported.

In the technology demonstration[58] shown in Fig. 2.28, a working 1911 design type firearm was 3D printed in solid metal and test fired to prove the concept. The company, Solid Concepts had produced other types of the handgun as a special issue then sold to consumers.

2.14 Hybrid Additive/Subtractive Systems

The integration of AM processing with advanced subtractive processing such as milling or turning is another area of technology development promising to leverage the best of both worlds. A new world of design opportunities exist in the marriage of two or more processes on the same build platform allowing a hybrid design relying on the strengths of each process.

Commercial systems integrating laser directed energy deposition within a precision machining platform have reached the market place. They offer the capability to add complex features or surfaces to simple base shapes or add to complex shapes

[58]Solid Concepts blog, https://blog.solidconcepts.com/industry-highlights/1911-3d-printed-guns-will-sell-lucky-100/, (accessed August 13, 2015).

[59]Courtesy of Solid Concepts Inc. under CC BY-SA 4.0: https://creativecommons.org/licenses/by-sa/4.0/deed.en.

already formed by CNC machining. DED-L is well suited for this application as laser powder feed heads can be made small enough to fit within the confines of these systems. These hybrid systems are being marketed as solutions for small parts needing complex features made from hard to machine materials or large workpieces with high stock removal volumes. One such hybrid machine the LASERTEC AM/SM system[60] made by DMG Mori, allows AM feature deposition and conventional milling within the same setup.

Another competing approach to hybrid systems incorporates a multi-turret milling platform into a PBF-L system to mill surfaces and contours deposited by PBF-L in an attempt to attain the desired accuracy while the part is being built. Other systems have demonstrated the use of robotically controlled tools to combine laser cladding with five-axis machining, in process measurement, polishing, annealing and cleaning all into one system setup.

The Hybrid Manufacturing technologies[61] Web site has a video that shows machining, laser cladding, on-machine gauging and post-machining operational sequencing all on one machine for the repair of a turbine blade as part of the UK RECLAIM project.

Lumex Advance-25 hybrid machine[62] by MC Machinery Systems, in partnership with Matsuura Machinery Corporation has created the LUMEX Avance-25 metal laser sintering hybrid milling machine combining metal laser sintering (3D SLS) technology with high speed milling technology, enabling one-machine, one-process manufacturing of complex molds and parts.

2.15 Key Take Away Points

- 3D printing and additive manufacturing of metal prototypes is now widely adopted with new applications being show cased across a wide range of industrial sectors.
- Custom, on demand, one of a kind personal items such as jewelry or consumer goods are now being offered commercially.
- Medical devices, surgical aids, and implants are being approved for use and can be matched to a person's anatomy. Unique surfaces and lattice structure offer benefits for bone ingrowth and biological integration.

[60]DMG Mori LASERTEC web link, http://us.dmgmori.com/products/lasertec/lasertec-additivemanufacturing, (accessed December 18, 2016).

[61]Hybrid Manufacturing Technologies Web site and video, http://www.hybridmanutech.com/, (accessed April 8, 2015).

[62]MC Machinery Systems, http://www.mcmachinery.com/whats-new/Matsuura-Lumex-Avance-25/, (accessed April 8, 2015).

- Dental devices with small lot sizes, high precision, and high value products are seeing wide adoption.
- AM Engineered aerospace components with complex internal structures, cooling channels, intricate lattice, and honeycomb features have shown the potential for significant energy savings, and the benefit of lightweight strong structures. Multiple conventionally produced components may be combined into a single AM part significantly reducing part count while cost savings are realized by improvements to the buy-to-fly ratio for expensive advanced materials.
- Industrial tooling and molds offer improvements to conventional production lines while repair and remanufacturing applications are improving and extending the life of legacy systems.
- Production of high-cost, low-volume components is focused on materials that are costly or difficult to process by conventional methods.
- Hybrid machines are leading the way to integrate AM capable machines into the digital factory.

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