# Additive Manufacturing Technology Assessment

## 1. Contents

# 1. Introduction to the Technology/System

## 1.1 Introduction to Additive Manufacturing

Additive manufacturing (AM) is the process of joining materials to make objects from Computer Aided Design (CAD) model data, usually layer upon layer, as opposed to subtractive manufacturing methods [1]. Additive manufacturing is also called as 3D printing, additive fabrication, or freeform fabrication. These new techniques, while still evolving, are projected to exert a profound impact on manufacturing. They can give industry new design flexibility, reduce energy use, and shorten time to market [2].

The current steps in AM are developing a 3-D model using a computer modeling software and converting the model into a standard AM file format, changing the size, location, or other properties of the model using AM software, then building the part in layers using the AM device [3].

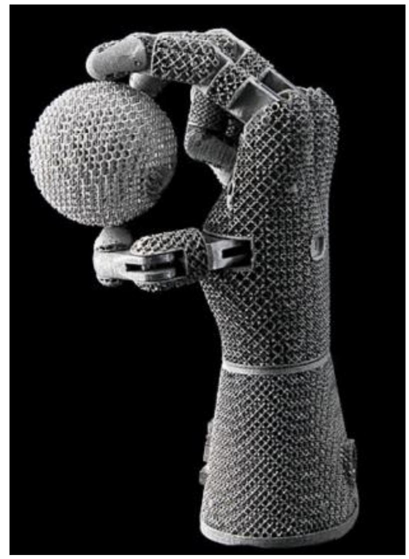


**Figure 1** - Titanium prosthetic hand produced at ORNL via Additive manufacturing [2].

Interest in additive techniques has grown swiftly as applications have progressed from rapid prototyping to the production of end-use products. Additive equipment can now use metals, polymers, composites, or other powders to “print” a range of functional components, layer by layer, including complex structures that cannot be manufactured by other means [4].

## 1.2 Additive Manufacturing Processes

Various AM processes have been introduced to the commercial market by industrial companies, including the Electro Optical Systems (EOS) in Germany, Arcam in Sweden, MCP Tooling Technologies in the UK, and Stratasys, 3D Systems, Optomec, and Z Corporation in the United States, among others [6]. There are several systems to classify the AM processes, e.g., the one proposed by the ASTM F42 Committee classifies the AM processes into seven areas [1].

**Table 1** – The Seven AM Process Categories by ASTM F42 [1].

| Process Type | Brief Description | Related Technologies | Companies | Materials |
|---|---|---|---|---|
| **Powder Bed Fusion** | Thermal energy selectively fuses regions of a powder bed | Electron beam melting (EBM), selective laser sintering (SLS), selective heat sintering (SHS), and direct metal laser sintering (DMLS) | EOS (Germany), 3D Systems (US), Arcam (Sweden) | Metals, Polymers |
| **Directed Energy Deposition** | Focused thermal energy is used to fuse materials by melting as the material is being deposited | Laser metal deposition (LMD) | Optomec (US), POM (US) | Metals |
| **Material Extrusion** | Material is selectively dispensed through a | Fused deposition modeling (FDM) | Stratasys (Israel), Bits from Bytes | Polymers |

| | | | | |
|---|---|---|---|---|
| | nozzle or orifice | | (UK) | |
| **Vat Photopolymerization** | Liquid photopolymer in a vat is selectively cured by light-activated polymerization | Stereolithography (SLA), digital light processing (DLP) | 3D Systems (US), Envisiontec (Germany) | Photopolymers |
| **Binder Jetting** | A liquid bonding agent is selectively deposited to join powder materials | Powder bed and inkjet head (PBIH), plaster-based 3D printing (PP) | 3D Systems (US), ExOne (US) | Polymers, Foundry Sand, Metals |
| **Material Jetting** | Droplets of build material are selectively deposited | Multi-jet modeling (MJM) | Objet (Israel), 3D Systems (US) | Polymers, Waxes |
| **Sheet Lamination** | Sheets of material are bonded to form an object | Laminated object manufacturing (LOM), ultrasonic consolidation (UC) | Fabrisonic (US), Mcor (Ireland) | Paper, Metals |

The AM processes can also be classified based on the state of starting material used (see Table 2) [5].

**Table 2 –** AM Processes and working Principles [5].

| State of starting material | Process | Material preparation | Layer creation technique | Phase change | Typical materials | Applications |
|---|---|---|---|---|---|---|
| Liquid | SLA | Liquid resin in a vat | Laser scanning/ light projection | Photopoly-merization | UV curable resin, ceramic suspension | Prototypes, casting patterns, soft tooling |
| | MJM | Liquid polymer in jet | Ink-jet printing | Cooling & photopoly-merization | UV curable acrylic plastic, wax | Prototypes, casting patterns |
| | RFP | Liquid droplet in nozzle | On-demand droplet deposition | Solidification by freezing | Water | Prototypes, casting patterns |
| Filament/ Paste | FDM | Filament melted in nozzle | Continuous extrusion and deposition | Solidification by cooling | Thermoplastics, waxes | Prototypes, casting patterns |
| | Robocasting | Paste in nozzle | Continuous extrusion | – | Ceramic paste | Functional parts |
| | FEF | Paste in nozzle | Continuous extrusion | Solidification by freezing | Ceramic paste | Functional parts |
| Powder | SLS | Powder in bed | Laser scanning | Partial melting | Thermoplastics, waxes, metal powder, ceramic powder | Prototypes, casting patterns, metal and ceramic preforms (to be sintered and infiltrated) |
| | SLM | Powder in bed | Laser scanning | Full melting | Metal | Tooling, functional parts |
| | EBM | Powder in bed | Electron beam scanning | Full melting | Metal | Tooling, functional parts |
| | LMD | Powder injection through nozzle | On-demand powder injection and melted by laser | Full melting | Metal | Tooling, metal part repair, functional parts |
| | 3DP | Powder in bed | Drop-on-demand binder printing | – | Polymer, Metal, ceramic, other powders | Prototypes, casting shells, tooling |
| Solid sheet | LOM | Laser cutting | Feeding and binding of sheets with adhesives | – | Paper, plastic, metal | Prototypes, casting models |

### 1.3 Benefits of Additive Manufacturing

Additive manufacturing and traditional manufacturing face different trade-offs, with each process likely to play a role in the deployment of manufacturing capabilities. AM has the potential to vastly accelerate innovation, compress supply chains, minimize materials and energy usage, and reduce waste [2]. Below, we list some benefits of AM technology:

- **Lower energy consumption:** AM saves energy by eliminating production steps, using substantially less material, enabling reuse of by-products, and producing lighter products [5].

- **Less Waste:** Building objects up layer by layer, instead of traditional machining processes that cut away material can reduce material needs and costs by up to 90% [6]. AM can also reduce the "cradle-to-gate" environmental footprints of component manufacturing through avoidance of the tools, dies, and materials scrap associated with CM processes. Additionally, AM reduces waste by lowering human error in production [7] [8].
- **Reduced time to market:** Items can be fabricated as soon as the 3-D digital description of the part has been created, eliminating the need for expensive and time-consuming part tooling and prototype fabrication [5].
- **Innovation:** AM enables designs with novel geometries that would be difficult or impossible to achieve using CM processes, which can improve a component's engineering performance. Novel geometries enabled by AM technologies can also lead to performance and environmental benefits in a component's product application [9].
- **Part Consolidation:** The ability to design products with fewer, more complex parts, rather than a large number of simpler parts – is the most important of these benefits. Reducing the number of parts in an assembly immediately cuts the overhead associated with documentation and production planning and control. Also, fewer parts mean less time and labor is required for assembling the product, again contributing to a reduction in overall manufacturing costs. The "footprint" of the assembly line may also become smaller, further cutting costs [2].
- **Lightweighting:** With the elimination of tooling and the ability to create complex shapes, AM enables the design of parts that can often be made to the same functional specifications as conventional parts, but with less material [2] [8].
- **Agility to manufacturing operations:** Additive techniques enable rapid response to markets and create new production options outside of factories, such as mobile units that can be placed near the source of local materials. Spare parts can be produced on demand, reducing or eliminating the need for stockpiles and complex supply chains [5].

Figure 2 lists some common attributes of AM that distinguish it from traditional manufacturing and the effect of each of these attributes on companies' existing product offerings and supply chains. Although not obvious, some product-related attributes have a bearing on a company's supply chains, and vice versa. For example, "manufacturing of complex-design products" appears to be a closely product-aligned attribute, but it also has supply chain implications: Companies that are designing complex parts need to ensure the fit of that complex part with other components sourced from suppliers. In a similar fashion, companies need to consider the impact of each AM attribute on their products and supply chain structures.

| AM attributes compared to traditional manufacturing | Impact on product offerings | Impact on supply chains |
|---|---|---|
| Manufacturing of complex-design products | Very high | High |
| New products that break existing design and manufacturing limitations | Very high | High |
| Customization to customer requirements | Very high | High |
| Ease and flexibility of design iteration | High | Medium |
| Parts simplification/sub-parts reduction | Medium | Medium |
| Reduced time to market | Medium | Medium |
| Waste minimization | Medium | Medium |
| Weight reduction | Medium | Low |
| Production near/at point of use | Medium | Very high |
| On-demand manufacturing | Low | Very high |

| Potential impact | Very high | High | Medium | Low |
|---|---|---|---|---|

**Figure 2 –** Impact of AM attributes on Aerospace companies' product offerings and supply chain structures [38].

# 2. Technology Assessment and Potential

## 2.1 Applications of Additive Manufacturing

The development of innovative, advanced AM techniques has progressed greatly in recent years, yielding broader and broader industry applications [4]. Compared with subtractive manufacturing, AM is particularly suitable for producing low volumes of products, especially for parts with complex geometries [4]. AM processes also offer great potential for customization, such as fabricating personalized implants for hip and knee replacements. The AM market in 2013, consisting of all AM products and services worldwide, grew 34.9% to $3.07 billion. This compares to growth in 2012 of 32.7% to $2.275 billion [2]. Wohlers Associates conducted a survey of twenty-nine manufacturers of professional-grade, industrial AM systems (those that sell for $5k or more) and 82 service providers worldwide for their 2014 report on AM [2]. The survey asked

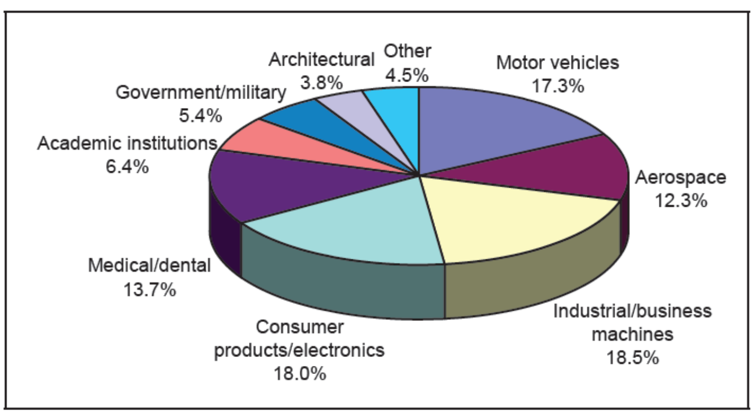



**Figure 3 –** Industries served by AM manufacturers and service providers [2].

each company to indicate which industries they serve and the approximate revenues (as a percentage) that they receive from each. The Figure 3 shows the results. The "Other" category includes a wide range of industries, such as oil and gas, non-consumer sporting goods, commercial marine products, and various other industries that do not fit into named categories.

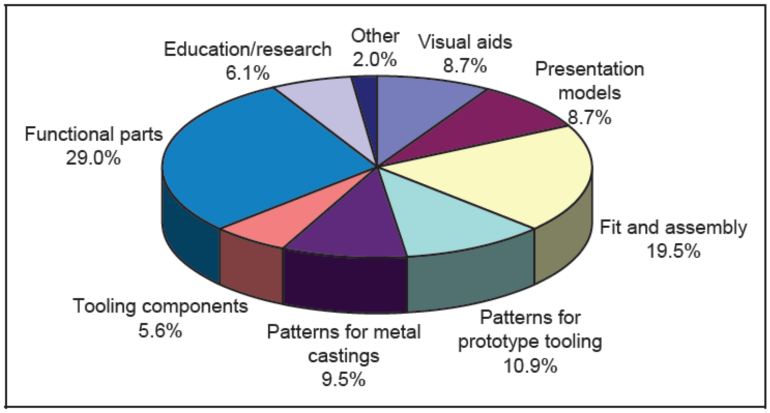



**Figure 4 –** How consumers use the parts built on AM systems [2].

The Figure 4 shows how organizations are using industrial additive manufacturing systems for range of applications. The survey results show that companies use AM technology to produce functional parts more than anything else (29%) [2]. The second most popular application for AM parts is as prototypes for fit and assembly (19.5%).

The market analysis shows that AM technologies are gaining more and more importance. An increasing number of industries benefit from the advantages of the technologies such as the freedom of design, and AM is progressively pushed from Rapid Prototyping towards small series production. Today, AM is already widely spread within known fields of application for instance within the aerospace and defense (A&D), automotive and electronics industry, and the medical sector including dental applications, prostheses, implants etc. [10]. Even, consumer industries such as the sports, the furniture or the jewelry industry are becoming aware of the advantages of AM-technologies for their business. As shown below, Figure 5 illustrates the global opportunities arising for 3D printing across many different industries [43]. However, the penetration of the industries by AM is still limited. To increase the penetration from today's point of view, the current, most relevant success factors across the analyzed industries are the following:

| | | Target user | | |
|---|---|---|---|---|
| | | Consumer | Small to mid-sized business | Corporations |
| Printer readiness | In need of further R&D | | • Organ Replacement, $30B | • Furniture, $20B<br>• Consumer electronics, $289B |
| | Nearing commercial use | • US Prepared food, $23B | • Bicycles, $6B<br>• Guns and ammo, $11B<br>• Global apparel, $1T | • Life sciences R&D, $148B<br>• Home building and improvement, $678B<br>• Power tools, $22B |
| | In use | • Craft and hobby, $30B<br>• Animation and gaming, $122B | • Medical prosthetics, $17.5B<br>• Retail hardware, $22B<br>• US Auto parts stores, $40B<br>• Toys, $80B | • Industrial R&D (for Prototyping), $23B<br>• Aircraft and defense R&D, $9B |

**Figure 5 –** Global opportunities for AM across industries [43]

- Design rules;
- Surface quality;
- Process reliability and part reproducibility.

The next sub-section provides a brief review AM applications in the aerospace & defense, automotive, electronics, tool and mold making, building, biomedical and energy fields.

### 2.1.1 Aerospace & Defense (A&D) Applications

Today, the development and research work within the A&D industry pursues the objective of continuously improving the efficiency of aircraft (this includes lightweighting of aircrafts) and reducing the air and noise pollution [11]. These objectives require parts that are lightweight, strong and electrically conductive in some cases [12]. In addition, most products are geometrically complex and manufactured in small quantities with high unit costs. Due to these special characteristics, the A&D industry is particularly suitable for an early adoption of AM [12], [13]. For instance, Boeing and Airbus are aggressively utilizing the AM-technology to reduce production time, build lighter-weight parts and reduce operational costs. Thanks to major progresses within several ranges, AM has already contributed to reduce or even to eliminate tooling, welding, inventory, and entire assembly lines [14]. The larger OEMs, are already trying to exploit these benefits for very large products; small companies are following.

Since 2009, the total AM-market (AM products and services) has grown by 64% [2]. The total volume in 2013 is around US$3.1 billion [2]. About 12.3% thereof is attributed to the aerospace industry (Figure 3) [2]. This corresponds to US$378 million [2]. Compared to the world market volume of the A&D industry amounting to $706 billion in 2013 [39], the AM-market share is still marginal. The world market size of the A&D industry is expected to double in size to US$1,200 billion by 2020 [39].

| | Current applications | Potential applications |
|---|---|---|
| Commercial aerospace and defense | • Concept modeling and prototyping<br>• Printing low-volume complex aerospace parts<br>• Printing replacements parts | • Embedding additively manufactured electronics directly on parts<br>• Printing aircraft wings<br>• Printing complex engine parts<br>• Printing repair parts on the battlefield |
| Space | • Printing specialized parts for space exploration<br>• Printing structures using lightweight, high-strength materials<br>• Printing parts with minimal waste | • Printing on-demand parts/spares in space<br>• Printing large structures directly in space, thus circumventing launch vehicles' size limitations |

**Figure 6 –** AM applications in the Aerospace and Defense industry [38].

AM is already being used for a great variety of applications within the aerospace industry (Figure 6). In particular, the design and manufacturing of lighter-weight parts play an important role for the aerospace industry. For instance, the following parts have already been manufactured additively:

- Structure parts for unmanned aircraft by SAAB Avitronics [15], [16];
- Special tools for the assembly [17];

- Customized interior of business jets and helicopters [15];
- Physical 3D mock-ups by Boeing [15];
- Turbine blades [14];
- Windshield defrosters by AdvaTech Manufacturing [12];
- Swirler - fuel injection nozzle for gas turbine applications by Morris Technologies, Inc. (now GE)

In addition, AM-technologies are used for reparation and remanufacture of worn component parts, such as turbine blade tips and engine seal sections e.g. by ROLLS ROYCE [18].

Different trends identified to be relevant for the A&D industry are listed below:

- Increasing usage of lightweight structures;
- Implementation of more organic features in designs for adding strength to components;
- Embedding additively manufactured electronics directly on parts [38];
- Increasing individualization of design and customization of the interior of aircraft;
- Intensified research in terms of developing new materials and differentiation features, e.g. individual cabin layout;
- Application of AM-technologies for tooling and fixturing;
- High pressure on the fuel-reduction technologies, e.g. laminar flow;
- Adaptive shapes, especially adaptive wings;

Table 3 provides an example on how AM enables weight reduction by optimizing design structure.

**Table 3** – AM enables weight reduction by optimizing design structure [45].

<table>
<tr><th>Traditional Design</th><th>AM Optimized Design</th></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">• A conventional steel buckle weights 0.34 lb (or 0.26 lb when made of aluminum)</td></tr>
<tr><td colspan="2">• Titanium buckle designed with AM weighs 0.15 lb – reduction of 55%</td></tr>
<tr><td colspan="2">• For an Airbus 380 with all economy seating (853 seats), this would mean a reduction of 160 lbs</td></tr>
<tr><td colspan="2">• Over the airplane's lifetime, 872 thousand US gallons of fuel or approx. US$2.3 million could be saved, assuming a saving of 5,390 gallon per lb and airplane lifetime</td></tr>
<tr><td colspan="2">• Project partners are Plunkett Associates, Crucible Industrial Design, EOS, 3T PRD, Simpleware, Delcam, University of Exeter</td></tr>
</table>

### 2.1.2 Automotive Applications

Today, the automotive industry is already a major user of Rapid Prototyping equipment: AM-technologies are being applied for manufacturing of functional prototypes and for small and complex parts for luxury and antique cars [10]. It's mainly because new product development is critical for the automotive industry, but developing a new product is often a very costly and time-consuming process. The automotive industry has been using AM technology as an important tool in the design and development of automotive components because it can shorten the development cycle and reduce manufacturing and product costs [4]. Especially, the motorsport sector constitutes an important field for the application of AM-technologies, as here high performance and low weight play a central role [10]. Within the automotive industry, increasing competition reinforces the pressure for reducing the time-to-market. This challenges the automotive industry to secure and further expand the market share. Against this background, the automotive industry can derive great benefits from the application of AM-technologies, as this technology enables a rapid production of complex parts, including a wide range of material properties.

In 2013, the automotive industry contributed 17.3% to the total AM market volume (Figure 3) [2]. This corresponds to approximately $531 million US dollars. Thus, the automotive industry is currently the major user of AM, as it accounts significant market volume, compared to all examined industries [2]. However, the AM-market is still marginal, compared to the world market volume of the automotive industry, which amounted to $2 trillion in 2013 [40].

AM is already widely spread within the automotive industry: it is being used for a great variety of applications, such as concept modeling, functional testing, rapid manufacturing, and production planning across the automotive industry [19]. However, AM is currently only used for prototyping and direct manufacturing of small, complex and non-safety relevant components within small series, as process reliability and consistency of products is still limited [14]. Furthermore, the construction size plays a central role, as many parts are oversized for being manufactured by currently available AM-machines.

Some examples for notable applications are named in the following:

- Testing part design to verify correctness and completeness of parts by BMW, Caterpillar, Mitsubishi [10], [20], [12];
- Parts for race vehicles, e.g. aerodynamic skins, cooling ducts, electrical boxes [21], [22], [15], [17];
- Pre-series components for luxury sport cars, e.g. intake manifolds, cylinder heads by Lamborghini [20], [19];
- Replacement of series parts that are defect or cannot be delivered, e.g. cover flaps by Lamborghini [20];
- Assembly assists for series production by BMW, Jaguar [12];
- Ducati engine by Stratasys, Inc. [41]

In the future, the automotive industry is expected to generate an immense demand for AM-equipment (see Figure 7) [10], [40]. Further trends within the automotive industry are:

- Higher demand for lightweight structures [16];

- Increasing demand of replacement parts for antique cars [21];
- Raising desire for individual mobility [11];
- Electrification of the power train [11];
- Higher focus on sustainable mobility [11];
- Increasing importance of individual customer needs [11];
- Higher density of traffic [11].

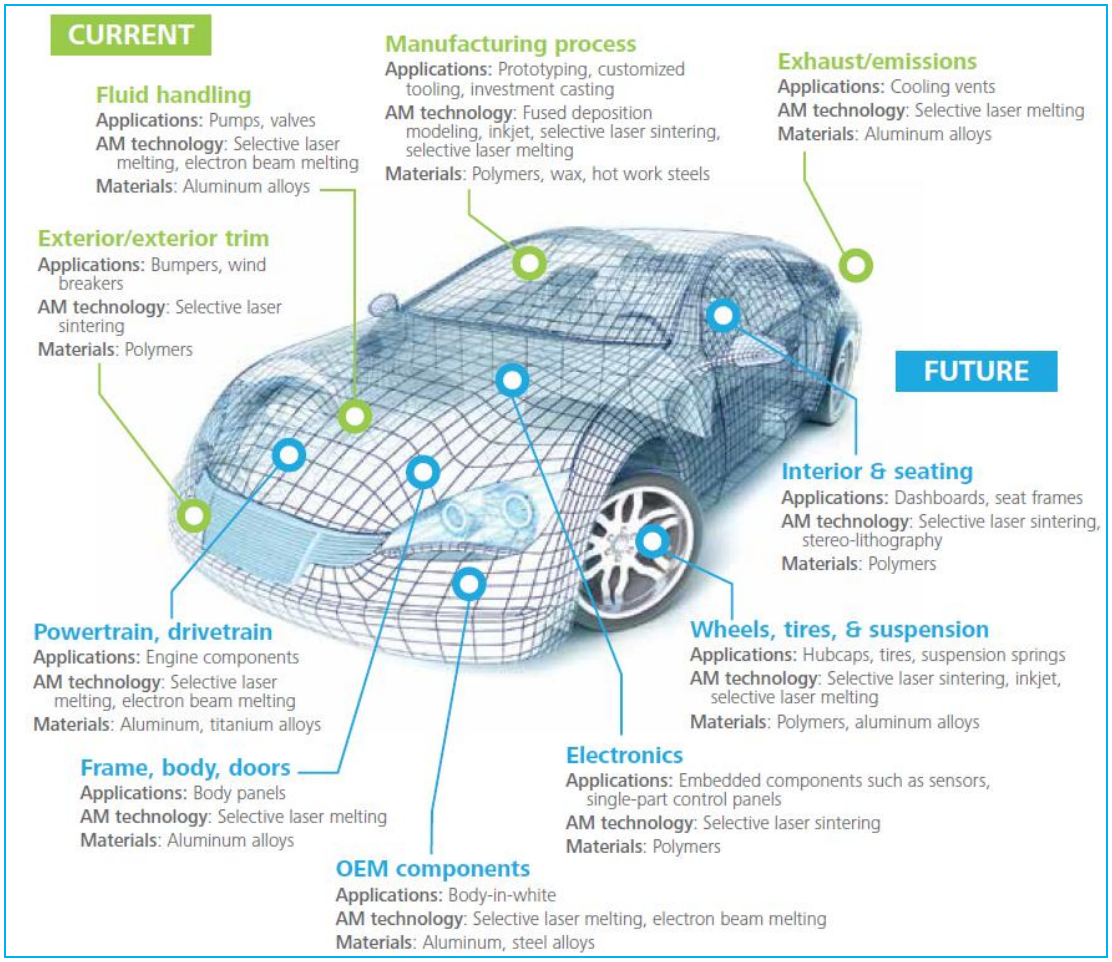



**Figure 7 –** Illustrative applications of AM in an automobile [40].

Delphi, a tier 1 automotive supplier, currently uses selective laser melting (SLM) instead of traditional machining of aluminum die castings to make aluminum diesel pumps (Figure 8). Through the use of SLM, Delphi not only was able to make the pump as a single piece—drastically reducing the part count and simplifying the assembly processes—it also reduced overall production costs. Producing pumps as a single piece also helped Delphi avoid several post-processing steps, resulting in a final product that is less prone to leakage [40], [49]. The pump housing shown in Figure 8 can be manufactured by conventional gravity casting and machining processes with a buy-to-fly ratio of 2:1. The same housing (same geometry) can be produced by Selective Laser Melting (SLM) process with a significantly lower buy-to-fly ratio (1.4:1). Table 4 compares the lifecycle energy consumption of a conventional production system with that of a selective laser melting AM process for aluminum as well as steel housing. The energy savings are primarily the result of significantly reduced buy-to-fly ratio enabled by additive process.

**Figure 8 –** Delphi diesel engine pump housing using selective laser melting [49]

**Table 4** – Mass and Energy comparison between automotive diesel engine pump housing (Delphi) manufactured by various pathways and materials [50]

| Manufacturing Pathway | Gravity die casting - Al | Selective Laser Melting – Al | Selective Laser Melting – SS 316L |
|---|---|---|---|
| Material input (lb) | 4.4 | 0.7 | 2.0 |
| Final part mass (lb) | 2.3 | 0.5 | 1.3 |
| | | | |
| Life cycle stage | | | |
| Raw materials (kBtu) | 305 | 64 | 68 |
| Manufacture (kBtu) | 5 | 28 | 87 |
| Transportation (kBtu) | 45 | 7 | 15 |
| Use phase (kBtu) | 324 | 73 | 209 |
| End of life (kBtu) | 1 | 0 | 0 |
| **TOTAL (kBtu)** | **681** | **173** | **379** |

### 2.1.3 Electronics Industry Applications

Electronics industry covers applications from mobile phones and computers to cars [10]. Electronics products are often small in size, and therefore, high precision tools are required for the manufacturing process. As technological advance is rapid, lifetimes of electronics are often short. Thus, new manufacturing equipment is needed in short intervals. Using new and flexible manufacturing technologies such as AM technologies is appropriate to accelerate development processes and build times [10]. All in all, AM can enable manufacturing equipment that can meet the challenge of the rapid technological advance, and to rapidly turn the advancements into new products [19].

Furthermore, the electronics industry is characterized by product miniaturization. Against this background, the integration of functions into structures is gaining importance. AM-technologies are suitable to meet these requirements though embedding electronics (circuits) into all kind of geometries [10].

AM is already widely spread within the electronics industry. Especially, the production of manufacturing and tools equipment benefits from the deployment of AM. The production of embedded electronics represents another field of application. Furthermore, AM is already used for products such as:

- Embedding Radio Frequency Identification (RFID) devices inside solid metallic objects [10];
- Polymer based, three-dimensional micro-electromechanical systems by MEMS [10];
- Microwave circuits fabricated on paper substrates [10];
- All kind of grippers within automated production systems [10]

The application potential for AM-technologies has been increasing significantly within the electronics production, as new polymers, and metal-based materials and inks have been emerging. Especially, inkjet printing methods are forerunners for the application of AM technologies within the electronics industry.

The total world market volume of electronics amounted to $5 trillion in 2013 [44]. In 2013, the consumer electronics industry contributed 18% to the total AM market volume (Figure 3) [2]. This corresponds to approximately $553 million US dollars [2].

Different trends identified to be relevant for the electronics industry are listed below [10]:

- Growing demand for accelerated product development requires shorter lead times of tooling;
- Focus on integration and services;
- Increasing demand for embedded electronics;
- Silicon electronics are increasingly becoming a key technology for information and communication technology;
- Miniaturization and functional integration of devices;
- Growing demand for smart microsystems;
- Emerging market for polymer electronics.

### 2.1.4 Tool and Mold Making Industry

Tooling includes moulds, dies and tools. The spectrum of tooling ranges from early-stage prototypes until full-scale production and is a capital and knowledge-intensive industry [16]. Aeronautics, automotives, electronics, household equipment goods and micro-devices are some industrial products wherein tooling contributes within the design and manufacturing process. Tooling is crucial for the competitiveness, efficiency and robustness of the production system of final products, as it links final parts (products and components) and production equipment (machine-tools) [16].

Today, the development and manufacturing of tooling is one of the most expensive and time consuming steps within any manufacturing process. This is mainly due to complex geometries of final parts that require high accuracy and reliability, low surface roughness, and strong mechanical properties [19], [23]. Furthermore, tooling strongly depends on its further application, as different applications require different materials, part volume, size etc. [16].

Within recent years, more and more companies have identified AM to be a promising technology to save time and money [16]. AM can contribute in different ways within the tooling industry: On the one hand, AM can be applied for the production of tooling. On the other hand, AM can function as tooling substitute. Both deployment possibilities provide numerous advantages compared to conventional manufacturing technologies. AM facilitates the manufacturing process, for instance regarding the cooling channels within the tooling. Using traditional methods, the channels need to be drilled into the tooling. Due to the notch effect, this process creates stress concentrations. This negative effect can be counteracted by AM, as AM-technologies enable the production of tooling (“Rapid Tooling”) with integrated cooling channels in a single step, at lower costs and within a shorter time [10]. Thereby, the time-to-market can be reduced and the product development process can be shortened [10], [19].

In 2006, U.S. tool, die, and mold shipments were at $13.35 billion ($5.5 billion worth of industrial mold manufacturing and $7.85 billion worth of special die, tool, die set, jig, and fixture manufacturing). The U.S. tool, die, and industrial mold industry is comprised of approximately 6,300 small and medium-sized businesses that manufacture highly customized tools, dies, and molds for use with machine tools and other types of production machinery [46]. The tooling industry belongs to the secondary market of AM, which includes tooling produced from AM-patterns and AM-systems, as well as molded parts and castings. Since last few years, the AM-market for tooling has grown. In 2013, the total volume was around approximately $172 million US dollars (5.6% of total AM-market, see Figure 4). Compared to the primary market volume, the AM-market volume of the tooling industry is considerable. Thus, the manufacturing of tooling and molds is one of the most anticipated applications for AM [24].

Despite serious competition within the tooling industry regarding conventional technologies, AM is already widely spread within the tooling industry, as reflected by the positive market development [10]. Conventional manufacturing technologies can be replaced or even eliminated in many cases. Paradoxically, the AM-technology substitutes itself regarding this field of application, as additive manufacturing of final products lowers the demand for tooling within small series production [10]. An example for direct tooling is the Fused Deposition Modeling (FDM) process. Due to improved variety and durability of AM-material, FDM can be applied to produce parts that require strength and durability. In the following, further applications that have already been realized are mentioned:

- Universal tool holders with standardized casting insert pocket sizes [10] [15];
- Die casting forms [10];
- Injection molding tooling [19];

- Models for investment casting [24];
- Fixtures for tooling [16];
- Tooling for prototyping of surgical devices [10].

The tooling industry can significantly benefit from AM, as AM can function as manufacturing technology and as substitute for tooling. For instance, AM enables a considerably shorter development and manufacturing process. This lowers the manufacturing costs significantly [25]. Thus, investments pay-off within a shorter period. In addition, AM-technologies are already applied for the manufacturing of die-casting models and enable a fast creation of complex geometries and shapes with a minimum of manual work [24]. Thereby, production times can be reduced and the quality of parts produced by using these models can be increased significantly. Finally, the replacement and maintenance of tooling becomes easier, faster and more cost-effective, especially as spare parts can be produced just-in-time.

The tooling industry is already one important industry for AM, as it can be used for manufacturing tooling as well as a substitute for expensive tooling equipment within different industries. However, within the recent years, the development of AM has been stagnating within the tooling industry, and less research on tooling applications has taken place [25]. The following trends have been identified for the tooling industry:

- The demand for accelerated product development requires shorter lead times of tooling [10];
- Efforts are made to reduce the break-even time of tooling [10];
- Increasingly, shorter life cycles of tooling are required to increase production of low-volume niche products [10];
- The deployment of universal tool holders and higher use of multi-component techniques while manufacturing small parts are increasing [10].

#### 2.1.5 Building Sector Applications

Currently, green homes prefabricated offsite save considerable resources over the average site-built home. However, they’re often shipped over long distances, upping the carbon footprint of even the most environmentally friendly materials. Additive manufacturing processes potentially can remove this problem. DUS Architects, a Dutch firm is aiming to use additive manufacturing to construct components of a complete house on site, using equipment housed in a shipping container, and work through the house room by room [26]. This building will then form the basis of a center for research into architecture produced by additive manufacturing [26]. If the house is a success and the technology honed, the architects hope that 3D printing could mark a new era in building houses. The cost of transporting materials and waste could be cut using the technique and the final buildings could be dismantled and moved in units, or completely recycled [47].

#### 2.1.6 Biomedical Applications

AM is suitable to contribute within this field of application, as the technologies enable production of items that are unique in terms of tailored to the patient’s requirements. Due to these capabilities of AM, there is great demand potential; especially equipment vendors can significantly benefit therefrom [15].

Research opportunities of AM technology in the biomedical field include the following:

- Create design and modeling methods for customized implants and medical devices.
- Develop viable Bio-AM (BAM) processes for fabrication of "smart scaffolds" and for construction of 3D biological and tissue models using living biologics.
- Create computer-aided BAM including modeling, analysis and simulation of cell responses and
- Medical research company Organovo makes functional human tissues using three dimensional "bio printing" technology [26]. In a press release dated 22 April 2013, they state that they "have achieved excellent function in a fully cellular 3D human liver tissue." Organovo's three dimensional "bio printing" technology was selected as one of the "Best Inventions of 2010" by TIME magazine. This is a major development in medical research and the potential impact these developments may have on the health care industry is immense. cell-tissue growth behavior [26].

In 2012, the market volume of the biomedical industry (implants and prosthetics) industry amounted to $121.6 billion, with an expected growth rate of 5.4 percent [42]. Regarding the AM-market, the medical and dental industry, has a market share of approximately 13.7% [2]. This corresponds approximately to $420 million [2].

### 2.1.7 Energy Applications

Ample opportunities exist for AM technology to contribute to the area of energy, such as through the rapid development and fabrication of prototypes to reduce the cost and lead-time of research and development of new products, and the exploration of novel designs to improve the energy efficiency and power density. AM is actively used in the manufacturing of fuel cells. For example, Bourell et al. [30] [31] developed an SLS based process to fabricate the graphite composite bipolar plate, which is one of the most important components in Polymer Electrolyte Membrane (PEM) fuel cells. By using SLS the cost and lead-time of developing new bipolar plates can be reduced dramatically compared to conventional methods such as injection molding and compression molding, in which expensive metal molds have to be manufactured. AM technology also expands the design possibilities and makes it easier to realize novel designs that might be able to improve energy efficiency and/or power density [4].

## 2.2 Challenges to Additive Manufacturing

To achieve a wider range of applications for AM, R&D efforts will need to overcome some key technical challenges, including the following:

- **Process control:** Feedback control systems and metrics are needed to improve the precision and reliability of the manufacturing process and to increase throughput while maintaining consistent quality [32].
- **Tolerances:** Some potential applications would require micron-scale accuracy in printing [11].
- **Finish:** The surface finishes of products manufactured using additive technology require further refinement. With improved geometric accuracy, finishes may impart corrosion and wear resistance or unique sets of desired properties.

- **Validation and demonstration:** Manufacturers, standards organizations, and others maintain high standards for critical structural materials, such as those used in aerospace applications. Providing a high level of confidence in the structural integrity of components built with additive technology may require extensive testing, demonstration, and data collection [11].
- **Conventional Manufacturing Bias:** Industry designers know the CM methods and use the conventional methods at a high level, so learning a new system faces resistance. Additionally many parts are optimized for CM, and facilities would need to slow production while installing AM systems [11].

The AM processes also face an array of market level challenges [38]. Figure 9 offers a snapshot of key AM market opportunities as well as challenges.

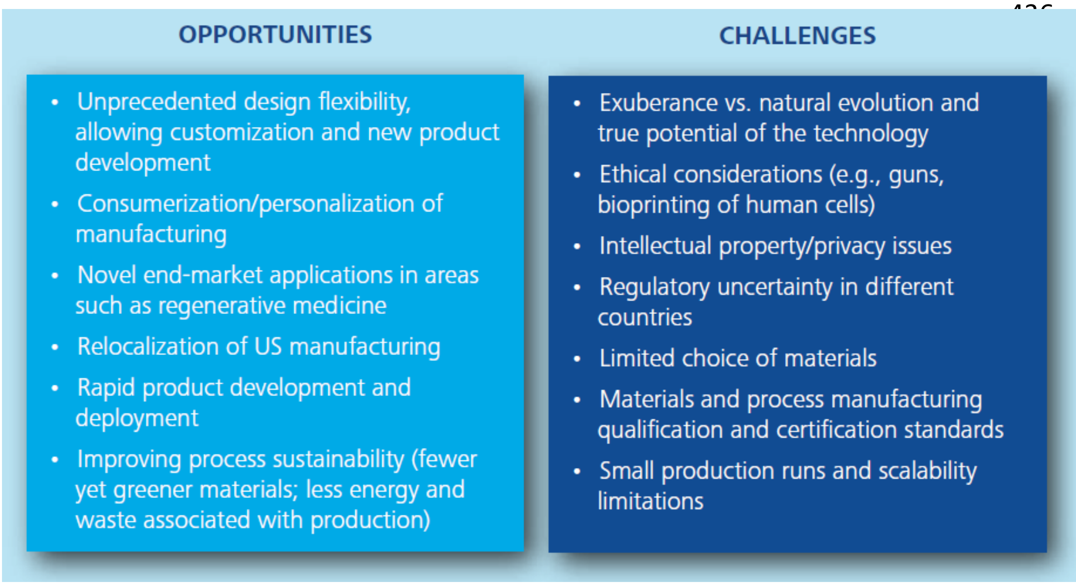



**Figure 9 –** AM opportunities and challenges [38].

### 2.3 Research and Development in Additive Manufacturing

Additive manufacturing continues to be a hot topic for research, driven by organizations like the National Additive manufacturing Innovation Institute (NAMII) (also called America Makes) and Manufacturing Demonstration Facility (MDF) at ORNL.

The following list covers the overall objectives of current R&D efforts in AM [2].

- **The freedom of design for the manufacturing parts** – efforts to produce meso-scale features, such as cellular structures, optimal designs, and textiles with repeated unit cells. A line of research dealing with micro-scale part production is also surfacing.
- **Sustainability** – Energy consumption, water use, and waste production are being studied.
- **Supply chain management and logistics** – Many studies and reports currently underway look at AM from the context of the ongoing changes it is causing in the manufacturing industry and society in general. The effects of a disaggregated supply chain on the delivery of products and

services, and the location and nature of jobs associated with those effects, are examples that are becoming increasingly prevalent.
- **Qualification, validation, and verification of AM parts** – The increase is associated with the growing numbers of AM parts being used in service applications, particularly in the safety-critical areas of aerospace and biomedical.

The pervasive topics for AM research covered in the 2009 Roadmap for Additive Manufacturing [15] are briefly described below.

### 2.3.1 Design

The unique capabilities of AM processes, including their ability to fabricate complex shapes, tailor materials and properties, and handle functional complexities, greatly enhance the freedom of designers to explore novel applications of this technology. However, it is not easy for designers to take advantage of these capabilities. Industry has yet to improve design to the point where it covers the full range of resources manufacturing facilities require [15]. To address this issue, the following developments are needed:

- Create conceptual design methods to aid designers in defining and exploring design spaces enabled by AM, methods for simultaneous product-process design and multifunctional design, and methods by which to assess lifecycle costs and impacts of parts and products fabricated by AM [15].
- Produce a new foundation for computer-aided design systems to overcome the limitations of existing solid modeling in representing complex geometries and multiple materials [15].
- Composable simulation capabilities for primitive shapes, materials, material compositions, etc., multi-scale modeling and inverse design methodologies to assist in navigating complex process-structure-property relationships, and improved finite element analysis software that can make use of such capabilities [15].
- Create methods to model and design with variability: shape, properties, process, etc. [15].

### 2.3.2 Process Modeling and Control

The ability to achieve predictable and repeatable operations is critical. Process variability must be reduced, as must the sensitivity to process variations. To achieve this, research in the following areas is needed:

- Develop predictive process-structure-property relationships integrated with CAD/CAE/CAM tools [15].
- Create closed-loop and adaptive control systems with feed-forward and feedback capabilities. Control system algorithms must be based on predictive models of system response to process changes [15].
- Produce new sensors (process, shape/precision/surface finish) that can operate in build chamber environments and sensor fusion methods [15].

- Develop modeling systems that combine design and manufacturing. The ability to predict manufacturing outcomes would decrease defects and increase part quality [32].

### 2.3.3 Materials, Processes and Machines

Research opportunities in AM materials, processes and machines include the following:

- Develop a better understanding of the basic physics of AM processes to capture the complexity in the multiple interacting physical phenomena [15].
- Processes based on scalable and fast material processing methods, such as processes that can fabricate a line (e.g., ink-jet printing) or area (e.g., mask-projection) to greatly increase machine throughput [15].
- Create new, open-architecture controllers for AM machines and the development of reconfigurable, standard machine modules that could impact on the field [15].
- Exploit unique AM characteristics to produce epitaxial metallic structures, fabricate parts with multiple and functionally gradient materials, and embed components (e.g. sensors and actuators) during fabrication processes [15].
- Develop screening methodologies to answer the question as to why some materials are processable by AM and some are not [15].
- Develop tools for AM fabrication of structures and devices atom by atom and design for nano-manufacturing [15].
- Develop and identify sustainable (green) materials including recyclable, reusable, and biodegradable materials [15].
- Develop a shared, standardized third-party data repository that contains AM material standards for data format and analysis and leads to proper choice of AM materials [32].
- Develop standards and protocol for a round-robin build and materials testing [32].

Materials play a key role in all AM processes. Material requirements are impacted by the need to create feedstock, to be processed successfully by the fabricator coupled with post processing, and to manifest acceptable service properties [15]. While individual AM processes are limited to varying degrees based on these requirements, in broad terms, an impressive variety of materials may be processed using AM. Figure 10a shows a hierarchy of homogeneous material systems that have been demonstrated using AM

[15]. Figure 10b lists heterogeneous materials [15].

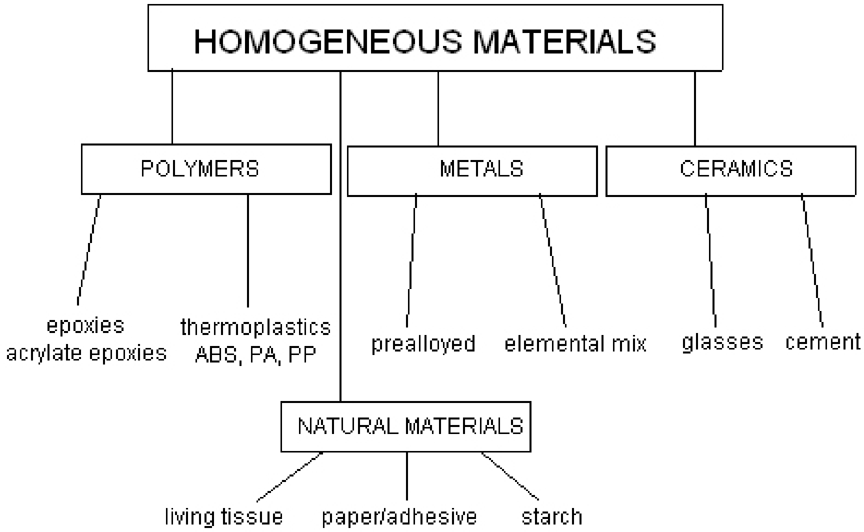



**Figure 10a –** A Hierarchy of Homogeneous Materials Systems for AM [15].

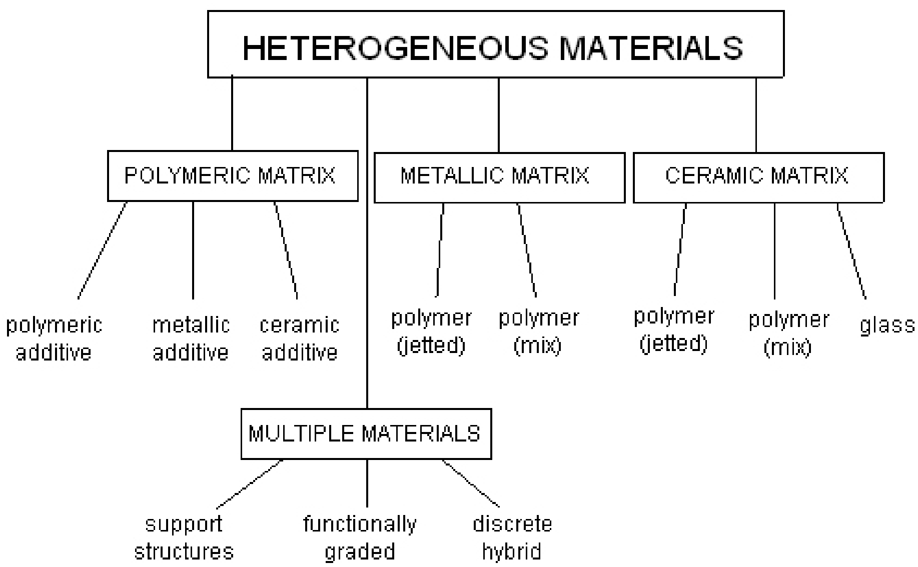



**Figure 10b –** A Hierarchy of Heterogeneous Materials Systems for AM [15].

- Biological composites represent an additional category to the hierarchy of materials. They have distinct structures on the nanometer scale that increase desirable properties such as toughness and strength. More R&D is needed to study rapid printing of macroscopic composites [35].
- AM has potential to improve on CM methods for complex parts made out of metal. AM can reduce waste by repairing worn metal (ex. Titanium) parts and by wasting less metal (ex. Steel) during manufacture of complex parts [36].

### 2.3.4 Energy and Sustainability related Implications

AM technology can save material and energy usage and lessen environmental burden compared with conventional manufacturing processes. Research opportunities relating to energy and sustainability include the following:

- Design energy system components to take advantage of AM capabilities [15].
- Pursue Maintenance, Repair, and Overhaul (MRO) as a potential AM application [15].
- Develop equitable indicators for measuring sustainability in AM processes and products [15].
- Develop cradle-to-grave lifecycle inventory of engineering materials for AM processes [15].
- Identify sustainable engineering materials for AM processes [15].

For example, LEAP jet engine from GE and Snecma incorporates fuel nozzles printed with laser sintering (see Figure 11) [48]. Conventional manufacturing process welds 20 parts to produce the fuel nozzle, while AM produces a single piece that is 25% lighter, five times more durable, and reduces fuel burn by 15% [33]. R&D in AM design tools enables industry to redesign parts for increased energy efficiency. With more than 6,700 orders from 20 countries, adding up to nearly $96 billion (U.S. list price), the LEAP is GE Aviation's best-selling engine in history [48]. GE's new plant in Auburn will be using direct metal laser melting (DMLM). The $50 million plant will operate several additive manufacturing machines simultaneously to meet demand, while employing approximately 300 workers at full capacity [48].

**Figure 11 –** The 3D-printed jet engine nozzles are five times more durable than the previous model [48].

### 2.3.5 Education

- Develop university courses, education materials, and curricula at both the undergraduate and graduate levels, as well as at the technical college level [15].
- Develop training programs for industry practitioners with certifications given by professional societies or organizations [15].

### 2.3.6 Development and Community

- Reduce machine, material and servicing costs to ensure the affordability of AM in relation to conventional manufacturing [15].
- Develop and adopt internationally recognized standards (such as those recently initiated by ASTM Committee F42) which are useful to product, process and material certification [15].

### 2.3.7 National Test-bed Center:

- Establish a national test-bed center with distributed AM machines and/or expert users to leverage equipment and human resources in future research and to exemplify the cyber-enabled manufacturing research concept [14].

# 3. Program Considerations to Support R&D

## 3.1 Public and Private Sector Activities to Date

The Figure 12 shows the growth in issued patents since 1995 and growth in patent applications since 2001. In 2013, the number of issued patents related to AM continued to increase linearly, while the number of patent applications decreased by 38 (4%). The number of patent applications had been increasing linearly since 2009 [2].

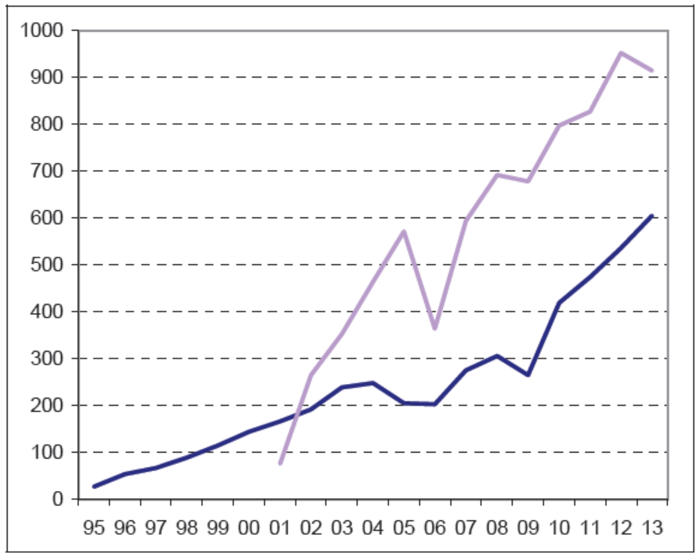



**Figure 12 –** AM Patents Submitted in Issued [6].

Non-competitive collaboration has played an important role in the development of the AM industry. The type of collaborations include user groups, online forums, and social media, industry roadmaps, industrial consortia, and even conferences and other events. Collaborations also occur among educational entities and working groups dedicated to establishing AM industry standards and educational curricula.

The following groups or organizations are playing important role in research and development of AM processes and technologies.

- America Makes
- U.S. Government Interagency AM Working Group
- Additive Manufacturing Consortium
- Direct Manufacturing Research Center (DMRC)
- ASTM International Committee F42
- Project TEAM (Technician Education in Additive Manufacturing)
- U.S. Government Sponsored R&D
- NSF Basic Research on Existing AM Technology
- Department of Defense
- U.S. National Laboratories (MDF at ORNL, LLNL)

# 4. Risk and Uncertainty, and Other Considerations

Identify and describe issues related to the following:

### 4.1 Risk and Uncertainty Issues

- AM industry may face intellectual property issues. It is likely that cheap access to additive manufacturing will further strengthen the power of internet distribution brands and channels at the expense of the originators of novel products [26]. The original data files created for the design of a product are difficult to protect by copyright law – and dealing with misuse of these files could be legally difficult. Much more problematic will be the creation of "rival" data files to create objects very similar to the original protected product where the scope of protection for the same work may vary in different countries [26].
- AM industry may need to deal with product liability issues. Collaboration and cooperation will be needed between original manufacturer, third party manufacturer, retailer, and regulator. In a world where additive manufacturing becomes commonplace, it will be up to the consumer to check that they are buying product design software from a reputable, traceable source. In that way, they will have recourse should a product they produce be defective and/or cause damage or injury [26].
- The variety of new materials introduced to AM (epoxy resins, elastomers, etc.) need additional studies to determine the long-term effects on humans and the environment [5].
- R&D into the solvents to remove AM material is needed because uncertainty exists over the environmental hazards, toxicity, and chemical degradation of current solvents [5].

### 4.2 Technology characteristics impact policy

- The sale of digital AM intellectual property such as STL files needs new tax regulatory policies, and state sales tax policies will need revision [29].
- AM supply chain developments will need definitions of taxable events for supplier and buyer[29]
- Economic unbalances should be investigated due to a decreased need for labor in manufacturing, and a change in global manufacturing [29].
- Open source AM technology would allow further development and improvement on the technology, but companies often protect IP to regain investments made in AM technology [29].

## 5. Sidebars and Case Studies

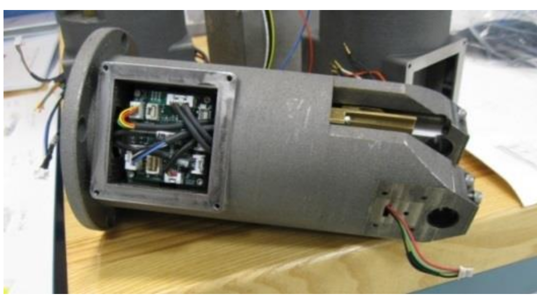
### 5.1 Case Study 1 – Application of AM technology for Robotic Systems

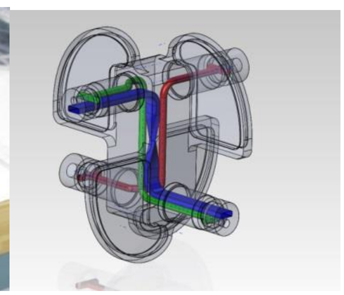
- Army PETMAN is an anthropomorphic robot designed for testing chemical protection clothing. Natural agile movement is essential for PETMAN to simulate how a soldier stresses protective clothing under realistic conditions. Boston Dynamics teamed up with ORNL in developing fully anthropomorphic android for in-situ testing of chemical and biological PPE. ORNL developed arms and hands using additive manufacturing technology. The PETMAN system has integrated sensing (chemical), perspiration, thermal management and control (hydraulics) and parts have complexity that would not be possible with conventional machining

Summary bullets:

- All components produced by additive manufacturing
- 25-lbs total weight, 60” long arm
- Neutrally buoyant without floatation
- Fluid passages integrated into structure
- 7 degrees of freedom with 180 degree rotation at each joint
- Custom thermal valves for energy efficiency

Robotic arm provided as backdrop in the White House as President Obama announced new two manufacturing innovation institutes.





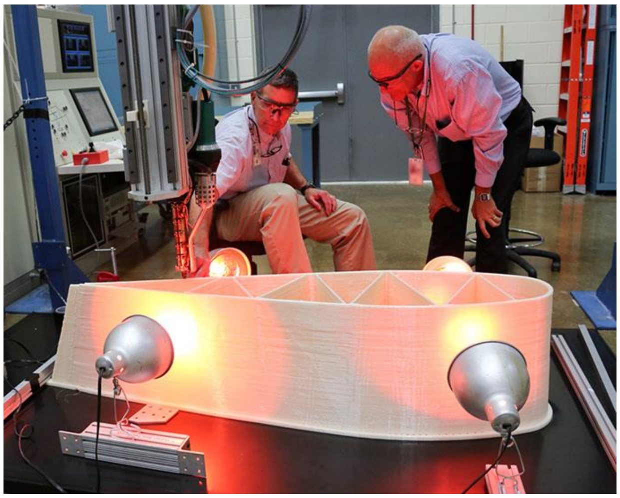
### 5.2 Case Study 2 - Large-Scale, Out-of-Oven Additive Manufacturing

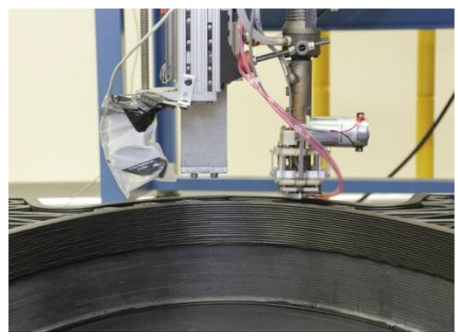
Big Area Additive Manufacturing (BAAM) – The driving vision for BAAM is a system that is unbounded by a build envelope and is capable of building thermoplastic parts outside of a controlled heat and atmospheric environment. The BAAM system combines melting, compounding, and extrusion through a material head attached to a large multi-axis robotic arm or a 3-axis gantry. Instead of pre-extruded filament feedstock, industry standard materials are used, such as injection-molding pellets, powders, fiber reinforcements, and specialty additives. An important part of the system is the inclusion of CNC milling to smooth the low-resolution surfaces.

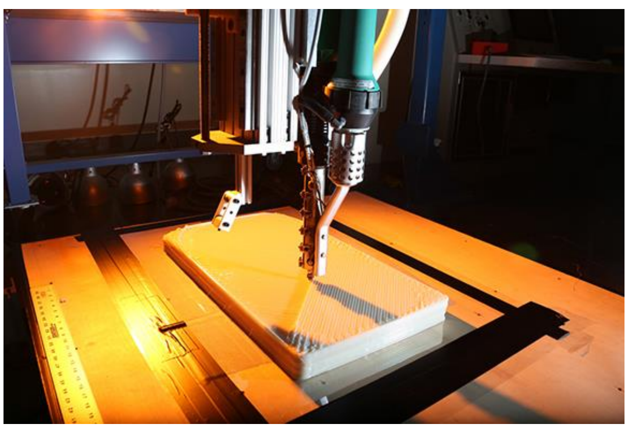
Summary bullets:

- Pellet-to-Part Pelletized feed replaces filament to enable 50x reduction in material cost

- Deposition rate 100x commercially available systems
- Tooling, UAVs, and robotics applications
- Prototype system 8’x8’x8’ build volume
- Huge initial interest by aerospace and composites industry







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