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Design for Additive Manufacturing: Trends, Opportunities, Considerations and Constraints

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Abstract

The past few decades have seen substantial growth in Additive Manufacturing (AM) technologies. However, this growth has mainly been process-driven. The evolution of engineering design to take advantage of the possibilities afforded by AM and to manage the constraints associated with the technology has lagged behind. This paper presents the major opportunities, constraints, and economic considerations for Design for Additive Manufacturing. It explores issues related to design and redesign for direct and indirect AM production. It also highlights key industrial applications, outlines future challenges, and identifies promising directions for research and the exploitation of AM's full potential in industry.

1. Introduction

The evolution of Additive Manufacturing (AM) over the past three decades has been nothing less than extraordinary. AM has experienced double-digit growth for 18 of the past 27 years, taking it from a promising set of uncommercialized technologies in the early 1980s to a market that was worth over $4 billion in 2014. The AM market is expected to grow to more than $21 billion by 2020 [354][355]. This growth has been made possible by improvements in AM materials and technologies and is being driven by the market factors that necessitate its use such as shorter product development cycles, increasing demand for customized and personalized products, increased focus and regulations on sustainability, reduced manufacturing cost and lead times, and the introduction of new business models [13][354][355].

During the past thirty years, the use of AM technology has also undergone a transformation. Early AM applications focused on models and prototypes [178][179]. As the technology matured, AM played a major role in producing rapid and soft tooling (e.g. vacuum and silicone casting molds) [187]. Today it is also used for the production of end use parts and products. It is estimated that the market for AM end use parts was worth $1.748 billion in 2014 - up 66% from the previous year. Strong double-digit growth in this area is expected to continue for the next several years [355]. Leveraging the geometric and material freedoms of AM for end use parts creates a world of opportunity. However, not all parts are possible or cost effective to produce using AM. This necessitates a better understanding of when, why, and how to (re)design for the opportunities and constraints associated with these technologies.

The CIRP community has previously reported on advances in AM processes [178][179][187][181][152], their role in rapid product development [42], and how they have been used in the biomedical [36] and turbomachinery [176] industries. This paper explores the opportunities, constraints, and economic considerations related to Design for Additive Manufacturing (DfAM). It begins with a brief overview of Additive Manufacturing, Design for Manufacturing, and the need for DfAM. It presents the main design opportunities, considerations and constraints related to AM technologies, including production time and cost. It presents DfAM success stories from a number of industries. Finally, it identifies promising directions for research and development that will enable Design for Additive Manufacturing to reach its full potential in industry.

2. Additive Manufacturing

Additive Manufacturing processes produce physical objects from digital information piece-by-piece, line-by-line, surface-by-surface, or layer-by-layer [178][130]. This simultaneously defines the object's geometry and determines its material properties. AM processes place, bond, and/or transform volumetric primitives or elements (voxels) of raw material to build the final part. Each voxel's shape and size and the strength of the bonds between the voxels are determined by the raw material(s), the manufacturing equipment (e.g. the build platform precision, nozzle geometry, light or laser beam wavelength, etc.), and the process parameters (e.g. the nozzle temperature, light or beam intensity, traverse speed, etc.). The overall part geometry is determined by tool paths, projection patterns (digital masks), or a combination of the two. This allows AM technologies to fabricate parts without the need for intermediate shaping tools [155].

AM processes are characterized by increasing workpiece mass. They represent one of three major classes of manufacturing technologies, along with subtractive processes where the workpiece mass is reduced and formative processes where the workpiece mass is conserved [125][26]. Additive Manufacturing processes are also distinct from chemical and thermal processes such as etching, plating, oxidation, and heat treatment, which act on all exposed (reactive) surfaces and traditional processes to create composite materials.

2.1 History of Additive Manufacturing

The foundations of Additive Manufacturing go back almost 150 years, with proposals to build freeform topographical maps and photosculptures from two-dimensional (2D) layers [40][256][48]. Research efforts in the 1960s and 70s provided proof of concept and patents for the first modern AM processes including photopolymerization in the late 1960s [356], powder fusion in 1972 [72], and sheet lamination in 1979 [243]. This work was enabled by the invention of the computer in the late 1940s, the development of photopolymer resins by DuPont in the 1950s, and commercial availability of lasers in the 1960s. It followed advances in computer aided design (CAD) and manufacturing (CAM), including the development of numerical control machine tools in the early 1950s, computer graphics and CAD tools in the early 1960s, CAD/CAM systems in the late 1960s, and the availability of low cost computer monitors starting in early 1970s [71][356][258]. However, the technology was in its infancy with no commercial market and little support for research and development activities.

The 1980s and early 1990s saw an increase in patents and academic publications; the development of new technologies such as MIT's 3D printing process in 1989 [130], laser beam melting (LBM) processes in the early 1990s [287], and the successful commercialization of process technologies including stereolithography (SL) in 1988; fused deposition modelling (FDM), solid ground curing, and laminated object manufacturing in 1991 [356]; and laser sintering in 1992 [287]. These advances were made possible, in part, by improvements in geometric modelling capabilities [71] and the development of programmable logic controllers [130] during the 1960s and 1970s, the development of ink jet printing technology in the late 1970s [130], and by the decreased cost and improved capabilities and availability of computers and CAD/CAM systems in the 1980s [256]. However, the high cost, limited material choices, and low dimensional accuracy of these machines limited their industrial application to rapid prototyping and model making.

The 1990s and 2000s were a period of growth for AM. New processes such as electron beam melting (EBM) [22] were commercialized, existing technologies were improved, and attention began to shift to developing AM related software. AM-specific file formats such as STL (StereoLithography), CLI (Common Layer Interface), LEAF (Layer Exchange Ascii Format), and LMI (Layer Manufacturing Interface) [256] were introduced. AM-specific software programs, such as Clemson's CIDES (1990) and Materialise's Magics (1992) were developed. New generations of commercial systems offered new and improved features. Quality improved to the point that Additive Manufacturing technologies could be used to produce patterns, tooling, and final parts. The terms 'Rapid Tooling', 'Rapid Casting', and 'Rapid Manufacturing' were created to highlight the ability to use Additive Manufacturing technologies for production. Cheap, powerful computers helped to make new generations of AM machines smaller and more affordable [131]. Advances in solid modelling software made it easy and inexpensive for students and professionals to design and model 3D objects. Finally, the Internet made knowledge sharing easy and supported the development of open-source hardware and software. This led to the development of the first hobby AM machines from the RepRap project in 2005.

The late 2000s saw the commoditization of the AM processes that were commercialized in the 1980s and were a period of growth for the younger metal-based AM processes. The expiration of key patents for a number of older AM processes opened the market to competition. This, combined with a growing AM hobby community, spurred innovation, leading to a major expansion of market supply and demand. Today, AM products and services support a wide range of activities including manufacturing, energy, transportation, art, architecture, education, hobbies, space exploration, and the military. Wide scale adoption of AM for the direct manufacture of final parts has occurred in the medical, dental, and aerospace industries. Meanwhile, commercial hobby printers and entry-level professional machines have made AM technology available to the masses.

If the current trends continue, we will soon enter a new stage of evolution where Additive Manufacturing becomes a design paradigm in addition to a means of production.

2.2 Digital workflow for Additive Manufacturing

Additive Manufacturing processes have a digital dataflow that generates the instructions for the AM machine followed by a physical workflow that transforms the raw materials into final parts (Fig. 1). The process usually begins with a product idea, a 2D image such as a photograph, a set of 2D images like those derived from Computed Tomography (CT) scans, or a physical 3D object like a prototype or a part for reverse engineering. These are transformed into digital models (e.g. volume models or facet models) using solid modelling, metrology, or image reconstruction software. Next, the data is checked for errors, the errors are corrected, and support structures are added if needed. This is often done with AM-specific software such as Magics from Materialise NV. Finally, the model is sliced or otherwise discretized to create instructions for the machine. This is often done using machine-specific software.

New software formats have been developed and standardized to support AM data preparation and digital workflow. For example, the AMF format, which has native support for color, materials, lattices, and constellations, has been standardized and is intended to replace the STL format. Other formats such as STEP, STEP-NC, and 3MF have integrated AM concepts to compete with AM-specific formats. Kim et al. [174] recently proposed a systems approach for data flow structuring and decomposition in several steps, clarifying the need for data generation and transformation along the AM digital chain.

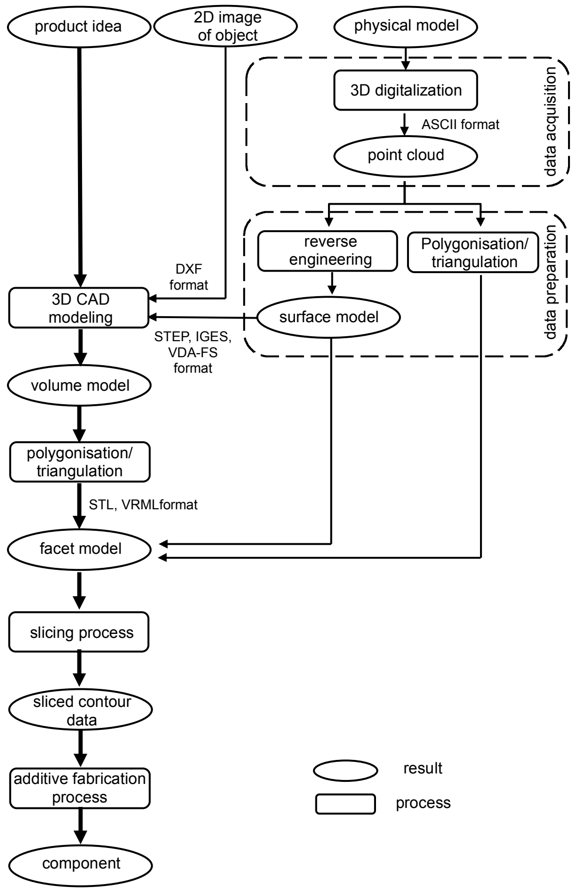

Fig. 1.Digital and physical workflow from product idea to actual component. Redrawn from [337].

Materials	Example materials	Process categories						
		Vat photo-polymer-ization	Material jetting	Binder jetting	Powder bed fusion	Material extrusion	Directed energy deposition	Sheet lamination
Thermoset Polymers	Epooxies and acrylates	X	X					
Thermo-plastic polymers	Polyamide, ABS, PPSF		X	X	X	X		X
Wood	paper							X
Metals	Steel, Titanium alloys, Cobalt chromium			X	X		X	X
Industrial ceramic materials	Alumina, Zirconia, Silicone nitride	X		X	X			X
Structural ceramic materials	Cement, Foundry sand			X	X	X		
Note: Combinations of the above material classes, e.g. a composite, are possible								

Fig. 2.Additive Manufacturing process families and materials [155].

2.3 Additive Manufacturing processes and physical workflow

The physical workflow begins with one of the seven currently recognized groups of AM technologies: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat polymerization (Fig. 2) [26][155].

AM processes can be used for the direct production of models, prototypes, end use parts, and assemblies, as well as fixtures, patterns, and tooling for indirect production [155][337][66][71]. AM can be integrated to create hybrid processes [163][166][168][182][317] or combined with other processes to form longer multi-stage process chains [149][327][337]. For example, parts can be printed to near net shape and then post-machined (Fig. 3), molds can be produced by alternating printing and machining operations (Fig. 4), features can be printed on top of formed components [14], and components can be embedded within printed parts (Fig. 5 and Fig. 6).

Each process family has distinct operating principles, production characteristics and compatible material types. These traits affect the cost, quality, and sometimes the color and scale of the parts that can be produced, and therefore can substantially impact design decisions. The consideration of process specific characteristics during the design process is even more important when AM is combined with other direct manufacturing processes (e.g. machining) and indirect manufacturing processes (e.g. molding or casting) [43].

2.4 Current AM standards

Working groups for the development of AM-related standards have been organized by the International Organization for Standardization (ISO/TC 261) and the American Society for Testing and Materials (ASTM F42). To date, they have produced standards related to terminology, individual processes, chains of processes (hardware and software), test procedures, quality parameters, customer-supplier agreements, and fundamental elements. Recent additions address data processing [156] and consider the relevance of and specify variations to existing standards [27][28] (Fig. 7). In 2013, ISO and ASTM defined a common goal to produce one set of global standards including general standards that are applicable to most AM materials, processes, and applications; category standards that define the requirements for a material or a process category; and specialized standards for specific requirements to a material, process or application [158]. AM standardization efforts are also taking place in Germany (VDI FA 105 and DIN NA 145-04-01AA), Spain (AEN/CTN 116), France (AFNOR UNM 920), Sweden (SIS/TK 563), the US (SAE AMS-AM) and the UK (BSI AMT/8). The Association of German Engineers published VDI 3404 and VDI 3405 as part of this work.

AM standards provide a common understanding of the field and a shared lexicon from which to work. This is important for developing and using AM-related design tools and methodologies. It is also a pre-requisite for developing design related AM standards. For example, ISO/ASTM DIS 20195 “Guide for Design for Additive Manufacturing” [157] is currently under development.

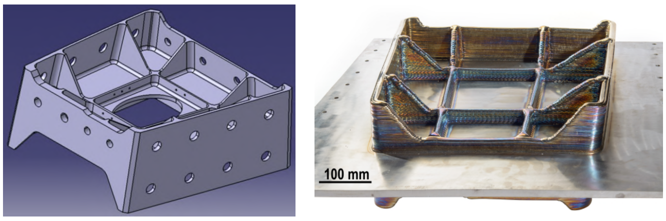

Fig. 3. Outboard landing gear rib (24 kg) produced in Ti–6Al–4V by Wire + Arc Additive Manufacturing (WAAM): CAD model (left, courtesy of the Welding Engineering and Laser Processing Centre at Cranfield University) and printed part before machining (right, [352]).

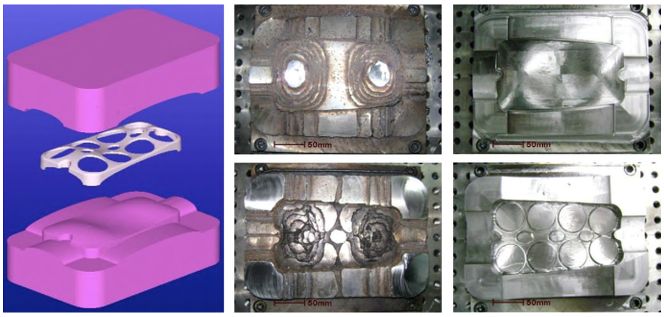
Fig. 4. Injection molding tooling produced by 3-axis Hybrid Layered Manufacturing (Gas Metal Arc Welding plus CNC machining): CAD model (left), near net shape molds (center), and finished molds (right) [317].

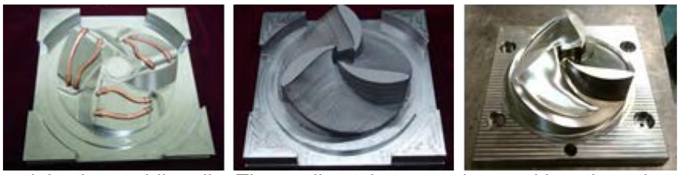
Fig. 5. Conformal cooling channels in an injection molding die. The cooling tubes were inserted into the substrate mold (left), the tubes were ‘buried’ and the die was completed using a laser-aided metal-based AM process (center), and the final tool was post-machined (right). Adapted from [59].

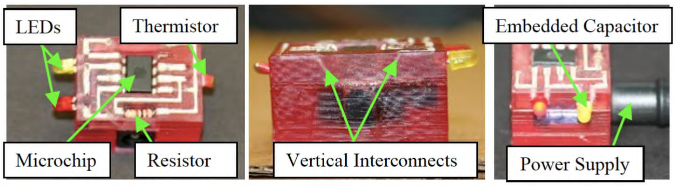

Fig. 6. Timer circuit with embedded electronic components produced using a hybrid stereolithography / direct print (SL/DP) machine [193].

3. Design for Additive Manufacturing

The term 'Design for Additive Manufacturing' has been used extensively in the literature [10][19][31][70][77][74][91][122][142][150][262][284][335][336], however there have been only a few attempts to define it [271][272][130]. This section provides an overview of classical Design for Manufacturing and Assembly (DfMA), examines the suitability of that definition and framework for AM applications, and outlines the need for the development of Design for Additive Manufacturing expertise and education.

3.1 Design for Manufacturing and Assembly

DfMA is the practice of designing and optimizing a product together with its production system to reduce development time and cost, and increase performance, quality, and profitability. This is done by "simultaneously considering design goals and manufacturing constraints" [168] such as "user and market needs, materials, processes, assembly and disassembly methods," maintenance requirements, etc. [228]. DfMA can be viewed from three levels of abstraction. At the first level, DfMA offers concrete tools, techniques, and guidelines to adapt a design to a given set of downstream constraints. These are usually process-specific (e.g. Design for Injection Molding) [46][260], feature-specific (e.g. how part size, weight, and symmetry affect insertion/assembly time) [46], or activity-specific (e.g. how to calculate the theoretical minimum assembly time) [45]. At the next level of abstraction, DfMA aims to understand and quantify the effect of the design process on manufacturing (and vice versa). This is needed to improve the performance of the manufacturing system, the execution qualities of the product (cost, functionality, customer satisfaction, etc.), the evolution (through-life) qualities of the product (safety, reliability, service and repair costs, etc.), and the long-term potential of the associated business case (e.g. the ability to respond to unexpected surges in product demand) [20]. In this context, DfMA is a subset of Design for X [183]. At the highest level, DfMA explores the relationship between design and manufacturing and its impact on the designer, the design process, and design practice. In this context, it addresses topics such as material and process selection, concurrent engineering [231][291], and how to improve CAD to support DfMA [46].

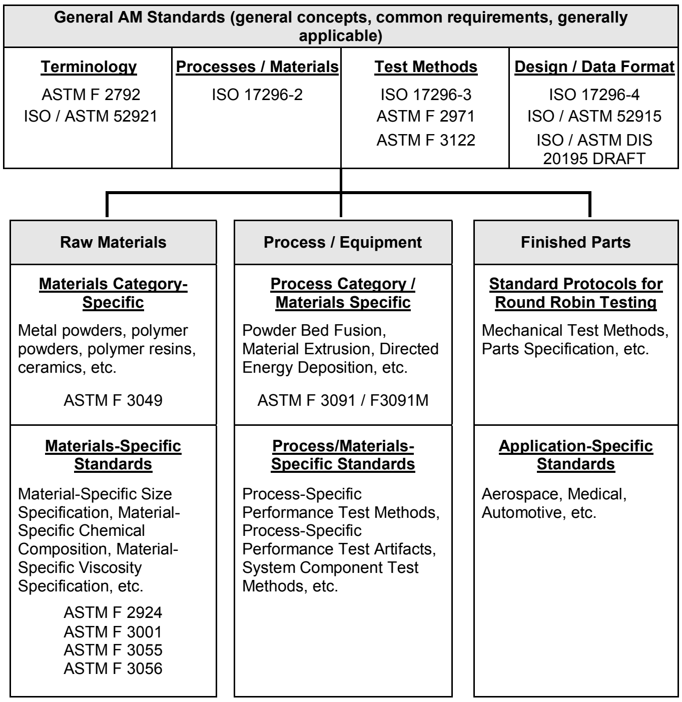

Fig. 7. ASTM and ISO standards for AM. Updated and modified from [158].

3.2 The need for Design for Additive Manufacturing

The definition of DfMA above is valid for all processes and process chains that involve AM. However, in practice the design knowledge, tools, rules, processes and methodologies at all three levels of abstraction will be substantially different for DfAM than traditional DfMA. For example, AM can create different types of features and impose different types of constraints than other manufacturing processes. Therefore, they require different process-specific design rules and tools [10][70][74][77][130][139][142][150][261][262][335] [336]. At the same time, the freedoms of AM reduce the need for, and therefore the importance of, designing for activities such as assembly [149]. AM processes have different batch sizes, production times, and cost drivers than traditional processes [29][148][275][276][366] and require different approaches to metrology and quality control [224][274]. Therefore a new body of knowledge is required to support DfAM. Finally, the unique characteristics of AM processes allow for and require different approaches to the design process and design practice [31][138][130][284][126]. This includes new approaches to explore large, complex design spaces [70][271][272][348]; to incorporate material, mesostructures and multi-scale design considerations [130][271][272]; and to overcome the "cognitive barriers" imposed by past experience and the conventional fabrication techniques [284].

The development of DfAM knowledge, tools, rules, processes and methodologies has been cited as one of the technical principle challenges of AM [19]. Insufficient understanding and application of DfAM is said to be limiting the overall penetration of AM in industry [122], holding back the use of AM for the production of end-use parts [10][122], preventing designers from fully benefitting from AM [91][126], and preventing AM from reaching its full potential in general [31][74]. Once Design for Additive Manufacturing is well understood, that knowledge must be disseminated to current and future members of industry. Thus, AM-specific design education [19][122][150] and design standards [19] are also needed.

4. Design opportunities, benefits, and freedoms of AM

This section provides an overview of design opportunities, benefits and freedoms associated with Additive Manufacturing. These have been divided into three levels: the part level with macro scale complexity, the material level with micro scale complexity, and the product level with multi-scale complexity. Production and business level benefits are discussion in section 6.

4.1 Design freedoms at the part level with macro scale complexity

Incorporating the material and geometric freedoms of AM into macro scale parts can provide a variety of aesthetic, functional, economic, emotional, and ergonomic benefits.

4.1.1 Material choice

AM technologies can process a large range of materials. Commercial AM machines can process polymers, metals, and ceramic materials [155]. Sheet lamination processes are compatible with paper, wood, cork, foam, and rubber [34]. Investment casting molds and cores have been printed in sand [343] and large structures have been printed in clay and concrete [171][173]. Research to print Lunar and Martian habitats using locally available materials such as lunar regolith is also underway [172]. Various AM processes have been used to print edible items such as chocolate, sugar, frosting, pasta, spreads, cheese, scallop puree, ground beef, egg whites, insect powders, and an entire pizza. Much of this work is motivated by the desire to produce novel shapes, flavors and textures; to provide personalized nutrition; to enhance the quality of life for individuals who have difficulty swallowing; to increase food supply security; and to improve dining in outer space [350][315][192]. (Some AM foods must be cooked, baked, or fried before consumption.) AM has also been used to print biological and bio-compatible materials such as cells, proteins, synthetic hydrogels, biological hydrogels, and bioactive glasses [36]. This work could ultimately enable additive manufacture of tissues and organs.

4.1.2 Color

Some AM processes can create products in full color (Fig. 8). This can be done by adding color to the raw materials (e.g. by ink jet printing on paper or powder), by using different color feedstock for different parts of the model, or by inducing color change in a single feedstock (e.g. resin) by in-process activation of pigments [169][263][318]. Additively manufacturing parts in color can reduce or eliminate downstream painting and decoration steps during production and reduce chipping and flaking. In rapid prototyping and model making, color can be used as a communication tool to highlight features such as tumors in medical models and to map analytical data onto objects to make the information easier to understand and discuss [303][332].

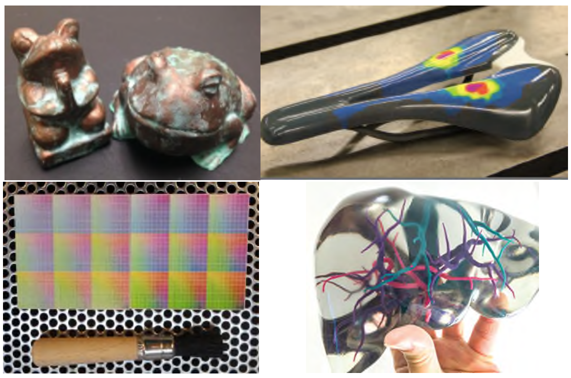

Fig. 8.AM objects in full color: frog and toad models printed using paper-based selective deposition lamination on an Mcor IRIS and colored to appear as aged copper (top left) [215]; bicycle seat colored to show simulated pressure distribution from a rider printed on an Objet Connex3 (top right) [294]; plates showing a 9x9x9 set of color options from a ZCorp ZPrinter 650 before and after brushing (lower left) [92]; and a surgical planning model of a human liver printed on an Objet Connex3 in clear and colored resins [303].

Fig. 9.Jewelery produced with AM: award winning Tiger Ring from OG-Art - pattern printed in wax on a Solidscape machine (via [34]) (left), Kinetic Ring from Vulcan Jewelry (available for purchase) (center, courtesy of Vulcan Jewelery); custom R2D2 inspired ring from Uptown Diamond and Jewelry - pattern printed in wax on a 3D Systems ProJet machine [4] (right).

Fig. 10.Home furnishings produced with AM: the Monarch Stool from Future Factories (left, via [90]), Quin.Mgx Pendant Light from Bathsheba Grossman printed in polyamide using SLS (available for purchase) (center, courtesy of Bathsheba Sculpture LLC), and decorative bowl by Carl Bass printed in stainless steel and bronze on an ExOne metal binder jet printer (available for download) (right, [114]).

Fig. 11.AM in the fashion industry: dress from Iris van Herpen's Voltage haute couture collection produced using laser sintering (left [208]), one-of-a-kind purse from Kipling produced using laser sintering (center, [210]), and Mutatio shoes by Francis Bitonti produced using SLS and then gold plated (available for purchase) (right, courtesy of Francis Bitonti Studio).

4.1.3 Freeform geometry for art and aesthetics

AM's ability to create unique, intriguing, and appealing geometric forms has led to its adoption by artists, artisans, and industrial designers. For example, AM is used in the jewelry industry for direct production [104][218] and to produce patterns for investment casting [94][97] (Fig. 9). It is also being used to enrich interior design with high-end furniture, lighting fixtures, and accessories (Fig. 10) and to explore new forms for clothing, shoes, purses, and other accessories in the fashion industry (Fig. 11). In the past, AM applications that emphasized form were mainly intended for exploration and exhibition. However, additively manufactured designs are becoming increasingly available for purchase and use.

4.1.4 Internal freeform geometry for functionality and performance

Additive Manufacturing enables the creation of complex internal features to increase functionality and improve performance. For example, AM has been used to create integrated air ducts [41][101][311][209] and wiring conduits [209] for industrial robots; 3D flexures for integrated actuators and universal grippers [134], complex internal pathways for acoustic damping devices [285]; optimized fluid channels (Fig. 12), and internal micro vanes for ocular surgical devices [69]. However, one of the most widely studied applications is conformal cooling. Conformal cooling channels follow the external geometry to provide more effective and consistent heat transfer (Fig. 13). Early research [280][359][129][267] showed that conformal cooling in injection molding tooling improves process efficiency and quality. Industrial injection molding case studies have confirmed these benefits with reports of reduced lead time, more uniform temperature distributions, reduced cycle times, improved quality, reduced reject rates, reduced corrosion, longer maintenance intervals, and overall cost savings [98][108][112].

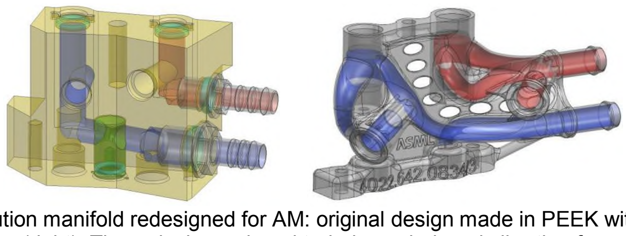

Fig. 12.Solid model of a water redistribution manifold redesigned for AM: original design made in PEEK with perpendicular drilled channels (left) and optimized version printed in titanium (right). The redesign reduced turbulence induced vibration forces by 90%. Images courtesy of ASML.

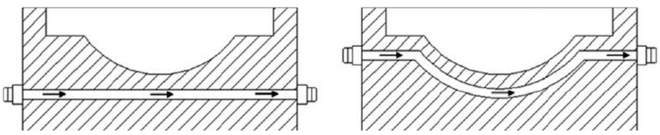

Fig. 13.Schematic of conventional cooling channel (left) and conformal cooling channel (right). Adapted from [17].

Conformal cooling is not limited to tooling. Fig. 14 shows two versions of a thermal conditioning ring from the semiconductor industry. The original design has circular cooling channels milled into the outer circumference of the ring and enclosed by a welded cover plate. The redesigned version was optimized for performance by incorporating additively manufactured conformal cooling channels on the top and side surfaces of the ring. The thermal behaviour of the two rings is shown in Fig. 15. The redesign improved temperature uniformity across the top surface of the ring by more than 6x, reducing the temperature range across the top face from 13.8 milli-Kelvin (mK) to 2.3mK and the temperature range over the thickness of the ring from 22mK to 3.7mK.

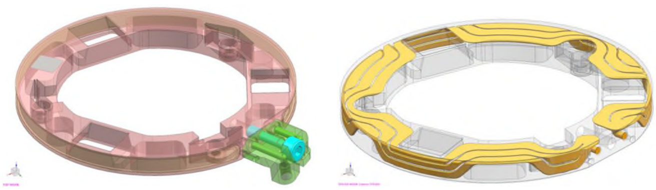

Fig. 14.Thermal conditioning ring with milled cooling channels enclosed by a welded cover (left) and with additively manufactured conformal cooling channels (right). Courtesy of ASML.

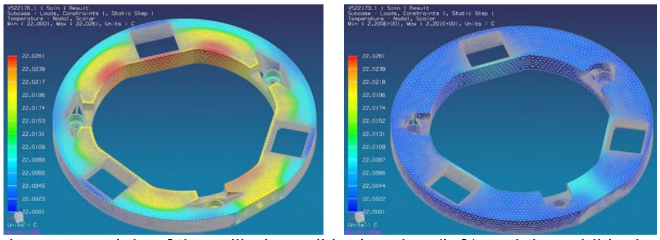

Fig. 15.Temperature plots from finite element models of the milled conditioning ring (left) and the additively manufactured conditioning ring (right). Shown with the same temperature scale. Courtesy of ASML.

Recent studies have focused on new applications of conformal cooling (e.g. hot sheet metal forming [240]), strategies for increased performance (e.g. profiled conformal cooling channels [17]), and indirect and hybrid AM for more efficient and cost effective production (e.g. using AM to produce wax patterns for indirect tooling [17], using machining for the less complex geometries followed by direct metal tooling for the part of the mold with the cooling channels [121], and using direct metal tooling processes to embed tubing inside near net shape molds [59] (Fig. 5)).

4.1.5 Production of macro-structure topology optimized objects for reduced material and energy use

AM can also produce macro-structure topology optimized objects. Topology optimization is a numerical approach that identifies where material should be placed in a given domain to achieve a desired functionality (e.g. stiffness) for a given set of loads and constraints while optimizing for qualities such as minimal material usage/weight or uniform stress distribution. Macro structure topology optimization assumes that the structure is composed of a single homogeneous material and that material is either present or absent in each part of the design domain. Although the optimization is often only in the structural domain, examples of multi-physics topology optimization (e.g. with thermal and structural degrees of freedom) can be found in the literature [119][135]. Macro structure topology optimization is especially useful in the aerospace and automotive industries [273] where weight reduction can lead to substantial energy savings over the usable life of the product. Aerospace related examples can be found in [23][49][241][329][105] (Fig. 16). Macro structure topology optimization has also been used to improve biomedical implants [61], investment casting processes [135], and more.

Fig. 16.Brackets before and after topology optimization: Airbus A320 nacelle hinge brackets as-designed for cast steel and optimized for titanium (left) and Airbus A380 brackets as designed and optimized for stainless steel (right) [105]. The optimized brackets were produced by direct metal laser sintering (DMLS).

4.1.6 Cost effective production of custom-fit and mass customized products

AM's direct digital workflow and freeform geometry can be combined to fabricate objects with any degree of customization (Fig. 17). This includes products that can be custom-fit to an existing person or object, products that can be personalized based on individual or group preferences, and mass-customized products that can be produced with infinite variations.

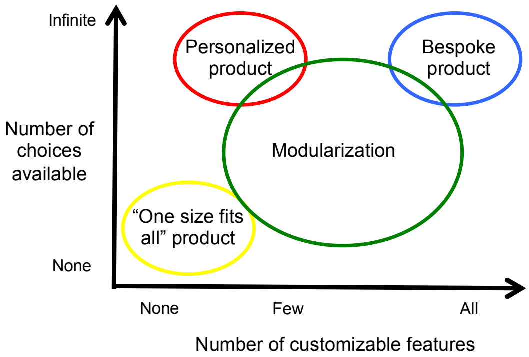

Fig. 17.Types of customization. Redrawn from [59].

In the medical and dental industries, AM is being used to produce a wide variety of personalized and bespoke products including hearing aids [214][93]; dental crowns, implants, and dentures [345][96][100] [102]; biomedical implants for hard and soft tissues [1][8][9][47][99] [103][107][111][330] (Fig. 18), customized casts, splints and orthotics [242][249][251] (Fig. 19), and prostheses [11][201][306]. AM is also used to produce patient-specific models to facilitate surgical planning [216][299][307][302][341] and surgical guides to improve accuracy and efficiency [95][301][305][309][310] (Fig. 20). For example, in orthopaedic surgery, cutting guides are used to correctly position an implant for the individual patient's anatomy. This improves the anatomical alignment of the implant and enhances the efficiency of the surgical procedure. AM surgical guides have the additional benefits of being lightweight (making them easier to handle during surgery) and disposable (safer).

Fig. 18.Titanium implants for the skull (left, [103]) and pelvis (right, [107]) produced using and EOSINT M 280.

Fig. 19.Customized laser sintered foot orthoses from Materialise's A-Footprint project (left) and customized selective laser sintered wrist splint produced by Fraunhofer IPA. Images via [251].

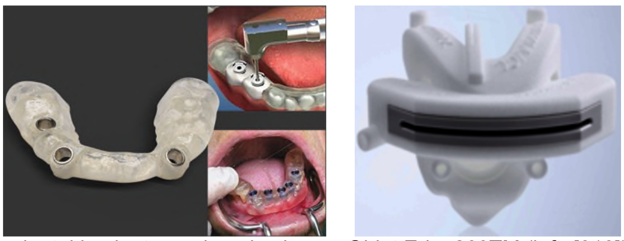

Fig. 20.Patient specific drilling guides for dental implants produced using an Objet Eden260TM (left, [310]) and cutting guide for knee arthroplasty (right, Courtesy of Aesculap AG).

AM is being used to produce custom-fit packaging and shipping materials. For example, the Pack & Strat process from CIRTES in France uses a sheet lamination approach to produce custom-fit low cost 'direct digital packaging' for fragile and high-value objects [34]. The process begins either with a CAD model or a 3D scan of the object to be packaged. The model is oriented and a bounding box is created around the model. The model is subtracted from the outer volume and the remaining volume is sliced. Next, the slices are arranged in sheets and the tool path is generated. Finally, the physical slices are cut from sheet stock, assembled around the object, bound, and placed in the shipping container (Fig. 21). This process is compatible with many types of material including cardboard, wood, cork, polystyrene, polypropylene, and foam. It has been used to package industrial components, machine tools, artwork, crystal, glass, prototypes, models, and more (Fig. 22).

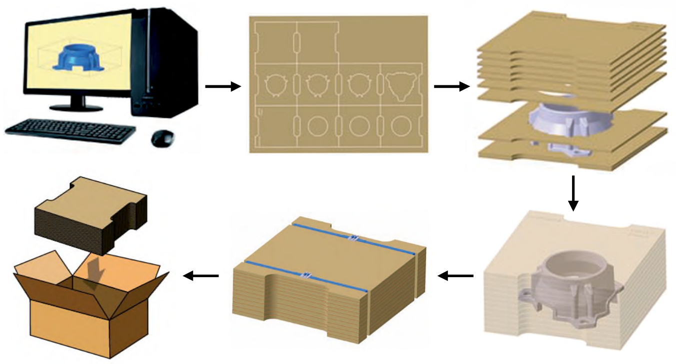

Fig. 21. Schematic of the Pack & Strat process. Adapted from [34].

Fig. 22.Examples of products with custom-fit packaging: metal industrial component with cardboard packaging (left) and wooden sculpture "Océane" by Dominique Pollès with alternating polystyrene and foam layers (right) [34].

AM is being used to produce custom-fit consumer products such as running shoes [110][206] and ear buds [308]; personalized products such as eye glasses with customized messages [213]; and bespoke objects such as 3D busts created from photographs or 3D scans [217][219][342]. Artists like Lionel Theodore Dean from FutureFactories.com are using AM to mass customize furniture, lighting fixtures, and other home furniture so each piece sold is unique. Finally, in the entertainment industry, AM is being used to produce mass customized models for stop motion animation [2][295].

4.2 Design freedoms at the material level and the micro scale

AM allows designers to modify and combine materials, micro-, and meso-structures to create new properties, forms, and functionality.

4.2.1 Custom metallurgy, microstructure, and material composition

Because AM simultaneously creates an object's material and geometry, it can be used to create custom alloys and composite materials. For example, it is possible to create custom mixes of powders and binders [353], to alternate feedstock materials [81][357], and to embed fibers [33][65][67] in order to create in situ composites, increase mechanical strength, modify the thermal expansion coefficient [67], and obtain electrically tuneable stiffness [281]. Similarly, it is possible to control the porosity, microstructure, and material properties of metal, polymer, and ceramic parts through the choice of materials, process parameters, and build orientation [75][292][353][362][365].

Postprocessing steps after each layer can also be used to control material properties. For example, Selective Laser Erosion and/or laser re-melting after each layer of a selective laser melting (SLM) process increases part density and reduces surface roughness [362]. Cold work by high-pressure interpass rolling of Ti–6Al–4V parts produced by SLM results in a refined, equiaxed, and texture-free microstructure [202][203] with mechanical properties that are higher than the forged material (ultimate tensile strength as high as 1078 MPa, and ductility up to 13%) [202]. Similarly, high-pressure interpass rolling of aluminium alloys during Wire + Arc Additive Manufacturing (WAAM) reduces porosity [136] and increases strength due to finer sub-grains and fewer mis-orientations [137]. Finally, postprocessing of finished parts can control and improve material properties. For example, heat treatment alters the grain structure and increases the mechanical strength of metal parts [164][349][357] (Fig. 23).

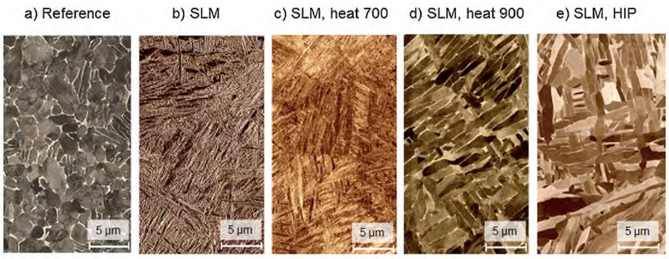

Fig. 23.SEM micrographs of etched surfaces showing the different grain structures of as-wrought (a) and SLM TiAl6V4 (b) with post heat treatment at 700°C (c), 900 °C (d), or hot isostatic pressing (e). Adapted from [164].

4.2.2 Custom surfaces, textures, and porosity for improved functionality

AM processes with micro or nano scale resolution can create custom surfaces, textures, and porosities. In the consumer product industry, AM has been used to produce prototype luggage with a textured shell [212]. However, the most important application today is the improved fixation and osseointegration of biomedical implants compared to porous coatings [78]. For example, AM porous metal acetabular augments are now widely used to address bony defects in patients undergoing revision total hip arthroplasty [319][351] (Fig. 24 left). Porous acetabular cups offer similar benefits [78] (Fig. 24 right). Implants with more complex surface structures for improved primary fixation are also being developed [7] (Fig. 25).

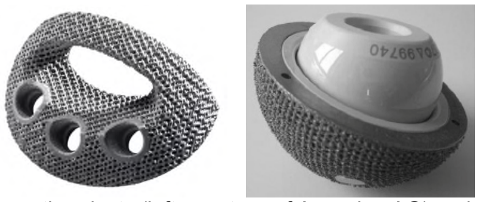
Fig. 24.Porous acetabular augment for hip revision arthroplasty (left, courtesy of Aesculap AG) and porous acetabular cup produced by EBM (right, [78]).

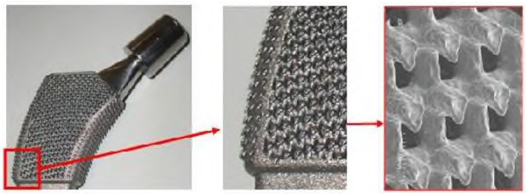
Fig. 25.OsteoAnchor^{TM} implant with micro scale features to improve primary fixation produced by DMLS [141].

4.2.3 Lattices, trusses, and cellular materials for custom material properties and biofunctionality

AM can create three-dimensional lattices and trusses with specific mechanical, thermal, optical, and biological properties. For example, AM lattices can be used to produce high stiffness low weight structures and photonic crystals (Fig. 26). Lattices and trusses can be incorporated into sandwich structures [360] or used to line external surfaces for increased strength [246]. Furthermore, enclosed lattices can be used as internal support for flexible structures such as inflatable (deployable) wings for unmanned aerial vehicles (UAVs) [197][198]. In structural engineering, the orientation and diameter of the individual struts within a truss or lattice can be optimized to improve stress distribution, strength, and manufacturability [268][323][324] (Fig. 27).

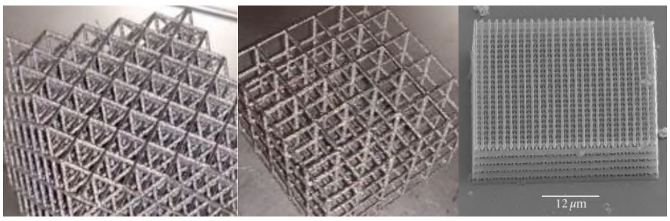

Fig. 26.AM lattices: octet truss lattice (left, [31]) and square lattice (center, [31]) produced using SLM, and photonic crystal with a micro woodpile structure made using two-photon polymerization (right, [247]).

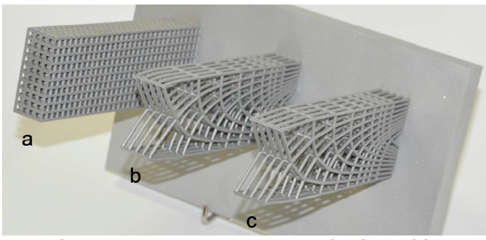

Fig. 27.Beams with lattice structures produced by SLM: periodic structure (a, left), flux of force adapted structure (b, center), and flux of force adapted structure with straightened struts (c, right) [324].

Cellular materials and structures are created by choosing the shape and volume fraction of a unit cell (Fig. 28) and building up a volume based on the unit cell (Fig. 29). Examples of unit cells are shown in [12][16][128][140][348]. The size, type, orientation, and boundary conditions of the periodic unit cell usually [12] (but not always [349]) affect the porosity, mechanical properties, and the deformation and failure mechanisms of the resulting materials. Therefore, the structure of the unit cell can be chosen or designed to produce specific material properties. For example, AM has been used to produce ultra light and stiff structures [374], auxetic structures [51][143][282] and the molds for the unit cells for auxetic structures [32], and could be used to produce the chiral honeycomb auxetic structures proposed by [177]. It has also been used to produce unit cells for acoustic materials with a negative refraction index [358]. In biomedical engineering, lattices can be optimized for cell attachment and growth; transport of nutrients and metabolic waste; biocompatibility, bioresorbability, and degradation; and biomechanical properties [151]. Examples of additively manufactured lattices in biomedical engineering can be found in [24][128][319]. The applicability of designer cellular materials and lattices for biomedical engineering, especially for the design and fabrication of orthopaedic implants and for bone and tissue engineering, is discussed in [21][24][78][88][128][151].

Various optimization methods exist for the design of periodic meso-scale cellular structures. Topology optimization is often used, but the designer has to consider issues of homogenization (the individual cell must be much smaller than the design space in all directions), and of periodicity (the material inside the cell must be such that it corresponds to the material in the adjoining cell). Manufacturing constraints, such as minimum wall thickness and minimum feature size, must also be considered. Although uniform lattices are common, there is no limit to the number of cell types and volume fractions that can be used. For example, structures can be topology optimized using different cell types and volume fractions [49][348]. Cellular lattices can also have spatial variations [120][279] (Fig. 30).

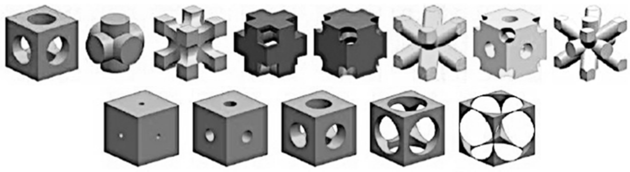

Fig. 28.Cell structures at 50% volume fraction (top) and an example cell with varying volume fractions (i.e. hole diameters) (bottom) [348].

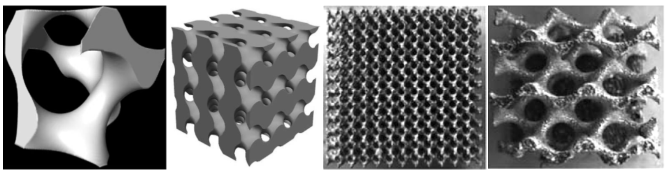

Fig. 29.Schoen Gyroid as a unit cell (left), volume generated from Schoen Gyroid unit cells (center left), Schoen Gyroid cellular structure with a 15% volume fraction and unit cell size of 2mm (center right), and with a unit cell size of 8mm (right). Both samples produced by SLM [140].

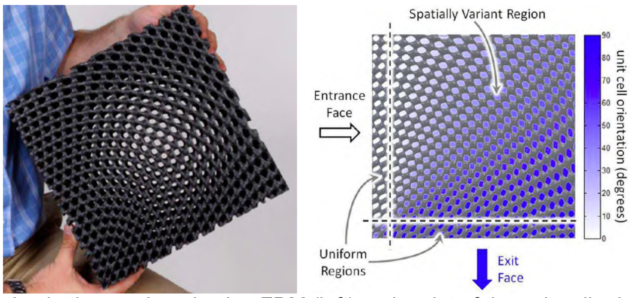

Fig. 30.Spatially variant self-collimating lattice produced using FDM (left) and a plot of the unit cell orientation over the part (right) [279].

4.2.4 Multi-material parts and products

Some AM processes can produce parts with different materials or material properties in different parts of the object. This is accomplished by using different feedstock or binders for different parts of the model. Multi-material AM has been used to fabricate wrist splints [251][252] (Fig. 31), compliant mechanisms [223], art [248], integrated electronics [333], and more. Multi-material AM can be used to produce multi-material topology optimized structures like those described in [123][145][266][338][346]. It could also be used to produce custom laminates and composites. For a review on multi-material AM, see [333].

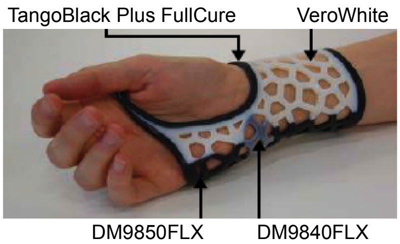

Fig. 31.Customized splint with multiple materials fabricated in a single build using an Objet Connex [252]

4.2.5 Functionally graded materials and objects

Some AM processes can vary the material percentage composition in different parts of the model to create functionally graded objects. The simplest case of this is to 'blend' a single material with void space to create variable porosity within a single body. However, most cases involve variable mixes of metals within an alloy system (Fig. 32 and Fig. 33), variable mixes of polymers (e.g. Stratasys Connex systems), or variable mixes of binders. While some AM processes such as the laser engineered net shaping (LENS) process and direct metal deposition (DMD) can produce continuous variations in a material, most others can only produce discrete variations within a layer or at layer transitions. For a review of functionally graded materials, see [289].

Fig. 32.Functionally graded flywheel (outer radius 0.2m) composed of 320 stainless steel and copper coated nickel produced using the LENS process [233].

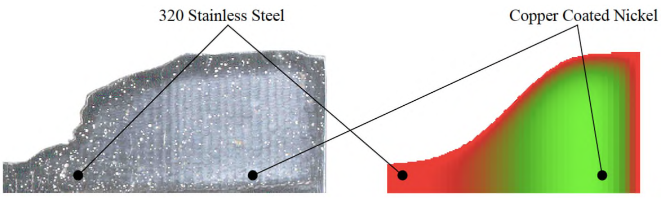

Fig. 33.Cross section of a functionally graded flywheel as designed (right) and as produced (left). The white spots are cavities that resulted from insufficient melting of the powder mix [233].

4.2.6 Metamaterials

Finally, AM could be used for on-demand production of metamaterials. Metamaterials are ordered composites that have material properties not usually found in nature [80][289]. Traditional metamaterials have a structured periodic lattice that interacts with an applied wave to produce unusual and useful properties such as artificial magnetism, negative refraction, near-field focusing, and more [52][289]. Today, most optical and electromagnetic metamaterials are produced using microfabrication techniques. However, 'mechanical metamaterials' whose properties are determined only by their structure (i.e. cellular materials) are being produced using AM in research settings (see section 4.2.3).

4.3 Design freedoms and opportunities at the product level

AM can provide additional design freedoms and opportunities at the product level including part consolidation, embedded parts, and the direct production of assemblies.

4.3.1 Part consolidation

AM allows designers to consolidate the parts of an existing assembly into a single printable object. This eliminates assembly time and reduces inventory costs. It can also increase functionality and improve performance. For example, GE Aviation redesigned the fuel nozzles for its LEAP engines for production with metal AM, reducing the part count from 18 to 1. This also reduced the mass by 25%, increased the durability by 500%, and improved efficiency by including features to reduce carbon build-up [355]. Other examples of part consolidation in the literature include a redesigned aircraft duct (reducing the part count from 16 to 1) [130], redesigned tractor control pod casing (reducing the part count from 6 to 1) [59], redesigned packaging for a medical injector system (reducing the part count from 15 to 7) [298], and redesigned robot grippers with flexible elements (reducing the part count from at least 9 to 1) [41].

4.3.2 Embedded objects and electronics

AM allows objects such as “small metal parts (bolts, nuts, bushings)” [130], tubes for cooling channels [84], and shape memory alloys for actuated hinges [83] to be embedded in printed parts. In addition, electrical components [146][193][195][253] (Fig. 6 and Fig. 34), conductive tracks [146][195][229][253][255], motors [130], batteries [200][316], and sensors [199][253][288] can be embedded or created in situ to print complete products and mechatronic devices (Fig. 34). The first commercial 3D printer with the ability to print conductive tracks and embed objects is scheduled to ship in 2016 [340]. For a review of sensor integration in AM, see [186].

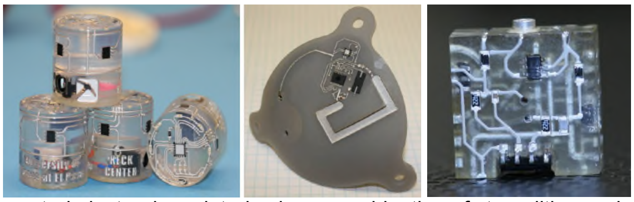

Fig. 34.Examples of AM objects with integrated electronics printed using a combination of stereolithography and direct print technologies [193] (left and center) [195] (right).

4.3.3 Direct production of assemblies

Finally, AM can directly produce assemblies with moving or movable parts such as crank and slider mechanisms [68], gears [56], joints [55][56][68] (Fig. 35), and hinges [29]. It can also produce “discontinuous interlinked structures” [79] (textiles) such as chain mail [44] and armor [162] (Fig. 36). AM textiles can offer “greater levels of out-of-plane and shear flexibility” than traditional textiles and can also be custom fit [79]. However, assemblies and interlinked structures require a clearance between the individual bodies during fabrication. They also require any remaining interstitial material (powder, resin, etc.) to be removed when completed.

Fig. 35.Articulated joints produced using selective laser sintering (SLS) [55].

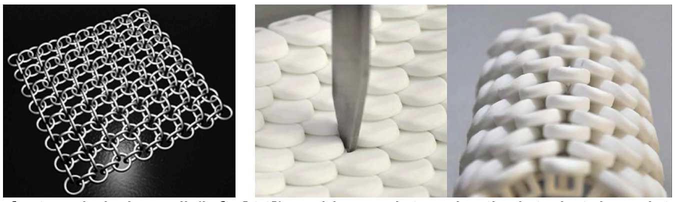

Fig. 36.Additively manufactured chain mail (left, [44]) and laser sintered articulated stab-resistant armor (right, [162]).

4.4 Discussion and limitations

Although all of the design freedoms discussed in sections 4.1 through 4.3 exist today, much of the work that was shown is still in the proof of concept stage. Research and development are needed on both the design and manufacturing side to bring all of these design benefits to the market.

5. Constraints and quality considerations in Design for AM

While AM seems to have unlimited potential, it does not have unlimited capabilities. Designers must take into account many types of constraints, including those associated with CAD and the digitization of their ideas; the digital and physical discretization of the parts to be produced; the characteristics of AM processes and the current capabilities of AM machines; the impact of AM processing on material properties and the requirements for processing materials using various AM techniques; new challenges and requirements associated with metrology and quality control; through-life requirements and considerations such as maintenance, repair and recycling; and external factors including the regulatory environment. While many of these constraints also apply to other types of manufacturing technologies, the bottom up nature of AM means they can have very different implications for designs, the design process, and the intermediate artifacts that are created to support production.

5.1 *Constraints associated with CAD and digitalization*

Today, AM is a highly automated direct digital production technique that discretizes a digital model of the artifact and generates machine ‘tool’ paths, digital masks, and other instructions to produce it. This imposes the first major constraint: designers must create comprehensive and complete digital models of the final product. Since there will be little or no human intervention in the translation of the digital model to the physical product, AM CAD models must be higher quality and contain more complete information than has been traditionally needed for other process technology.

Producing digital models for AM is challenging because most commercially available CAD programs are parametric NURBS systems. These are well suited to modelling geometries associated with traditional manufacturing processes (extrusions, revolves, lofts, etc.) but often inadequate for the more organic shapes [138] and complex, multi-scale geometries associated with AM. In addition, traditional CAD systems cannot generate multi-scale cellular and lattice structures, model or denote color, specify the material to use, indicate material variation within an object, or specify tolerances. To overcome these limitations, AM CAD systems require an interface that can develop complex shapes and structures, and a data structure that can store their properties.

Two common methods to overcome some of the bulk geometric limitations of legacy CAD systems are haptic modelling and reverse engineering. Haptic modelling is a virtual sculpting method that uses a force-feedback hand-held tool to interact with a 3D CAD model. It gives the user the sense that they are physically touching “virtual clay” [364] and therefore is much better suited to creating freeform shapes [57]. An alternative to developing the organic shape *ex nihil* is to start the modelling process by 3D scanning an existing physical object. This is particularly well suited for the development of models based on anatomical data [18] but it can also be used on hand-crafted models in clay, foam, or other materials. Next, the raw scanned data is refined. Then the shape can be developed further using a variety of digital tools. From this point on, the geometry is usually in the form of triangulated data rather than geometric primitives or NURBS surfaces. Regardless of how they are generated, 3D CAD models often need additional modifications and data preparation before they can be converted into machine instructions.

Options to model cellular and lattice materials and structures are more limited. Past solutions have involved complete solid models of truss structures using geometric modeling kernels such as ACIS [347], algorithms [24][88][140], and unit cell libraries [16][70][246] (Fig. 37).

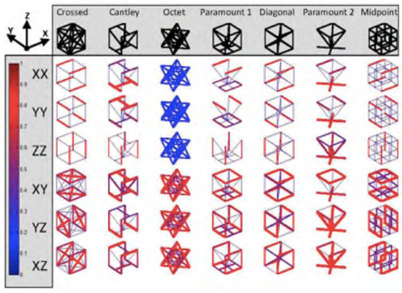

Fig. 37.Example of a unit cell library [246]

Researchers are working to overcome CAD and digitalization constraints by developing new data formats that can handle material related information. (For a review, see [333].) Multi-material capability has also been built into the AMF format. However, there remain many challenges when designing for heterogeneity taking into account the shape and material distribution in order to meet the functionality, requirements or constraints of the artifact. Issues include what granularity to consider during the design exercise, how to handle material variation analytically, and if the resulting design can be satisfactorily manufactured using a given AM process. The coupling between the design, representation, analysis, optimization and manufacture still needs to be resolved.

5.2 Constraints associated with discretization and directionality and the need for support and an appropriate build orientation

As noted in section 2, AM produces physical objects piece-by-piece, line-by-line, surface-by-surface, or layer-by-layer. This has several major implications for part quality and consistency.

5.2.1 The impact of discretization and orientation on surface roughness and material properties

The boundaries between the pieces, lines, surfaces, or layers of AM parts are rarely, if ever, seamless. This adds a characteristic roughness at the length scales associated with the discretization (Fig. 38, Fig. 39 Fig. 40).

Fig. 38.Benchmark showing the surface roughness resulting for SLM parts with different build angles. Courtesy of ASML.

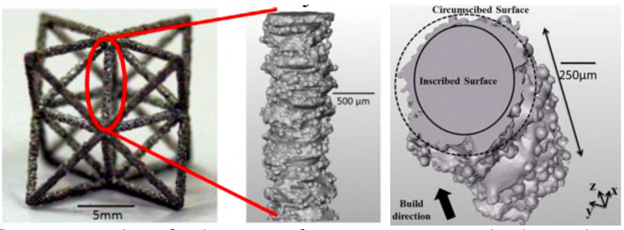

Fig. 39.EBM octet-truss unit cell (left), 3D reconstruction of a 1mm strut from x-ray tomography (center), and an isometric view of the strut showing the diameter variation by the inscribed and circumscribed diameters (right). Adapted from [314]. Note that the strut exhibits surface roughness at length scales associated with the layering and with the powder.

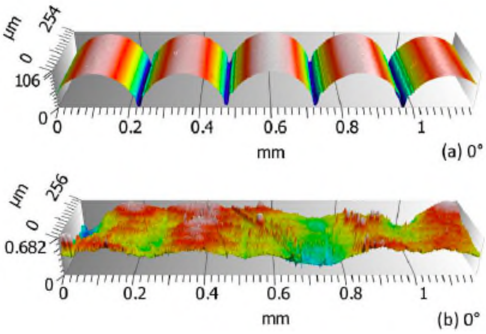

Fig. 40.Surface roughness of FDM parts deposited at 0° before (top) and after (bottom) chemical vapor polishing [50].

Since the characteristic lengths of the raw material and process parameters such as layer height are often at different length scales, the surface roughness is also often multi-scale [35][314]. The boundary between newly created and existing material can act as an interface where cracks and other types of failure can initiate. Since the discretization in modern AM processes is rarely isotropic, the surface roughness and resulting material properties [113][268][274] are also usually anisotropic. One common method to address these anisotropies is to modify the part [25][118][328] or assembly [232] orientation to minimize their impact. Other options include finishing operations after each layer [362] (Fig. 41), finishing operations such as chemical [35][254] (Fig. 40) or mechanical polishing, or post machining after the build is complete.

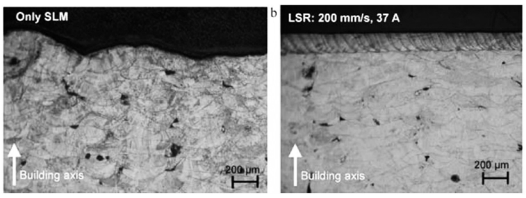

Fig. 41.Cross section of a surface created using SLM only (left) and SLM plus laser re-melting. Adapted from [362].

5.2.2 The need for support structures during production

Additively manufactured artifacts go through a large but finite number of states during the printing process. Each state must be able to resist the forces that are applied to it, including gravitational body loads, external forces applied by the printer, and internal forces from thermal and residual stresses. While this is also true for subtractive processes like machining, machined parts are usually in their strongest state at the beginning of the process and in their weakest state at the end. In contrast, AM parts are usually strongest when complete. Designers typically compensate for these mechanical effects by orienting the part to maximize its strength during the build, by adding support structures to the part, or by designing the part to be self-supporting throughout the printing process. All of these strategies can increase the cost and time of production. For example, Leary et al. [185] produced topology optimized cantilever beams with and without support structures using FDM (Fig. 42 and Fig. 43). The optimized beam without support required 1.6 hours to print and consumed 47.8 cm^3 of build material but did not print successfully. The optimized beam with columnar support required 5.7 hours to print and consumed 47.8 cm^3 of build material plus 41.9 cm^3 of support material. The self-supporting beam required 2.6 hours to print and consumed 54.9 cm^3 of build material.

Support strategies are always process specific. In some processes, the raw material (e.g. powder or resin) acts as a natural support. Some processes require a sacrificial build plate and/or support structures to anchor the part to a build plate. In these cases, support cannot be eliminated entirely. In metal AM processes the support acts as a pathway for heat conduction. Thus, support is often needed to counter the effects of thermal residual stresses and reduce heat related failures, even if the part is mechanically self-supporting. In these cases, the support must be designed to fulfil both the mechanical and thermal requirements [73][160].

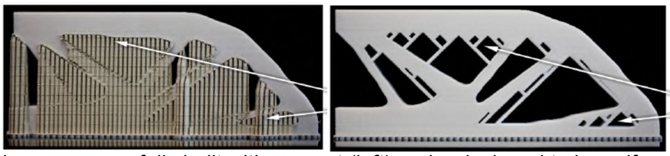

Fig. 42.Topology optimized cantilever beam successfully built with support (left) and redesigned to be self-supporting (right). Arrows indicate where build failures occur if no support strategy is implemented. Adapted from [185].

Fig. 43.Closeup of build support strategies: failed build with no support (left), successful build with support (center), and successful build of self-supporting structure (right). Adapted from [185].

Designers must also consider if and how the support will be removed and the impact removing it will have on the final part quality. For example, in self-supporting processes, the supporting material can become trapped in internal voids and may have to be removed from blind holes. In addition, removing the anchoring and support material and other postprocessing steps add risk to the part and can scar or damage the part [327]. Therefore, the choice of process and the anchoring and support strategy can affect the quality of a part even after the fabrication phase of production has finished.

5.2.3 Reducing process constraints to create new opportunities

Over time, process characteristics will relax and machine capabilities will be extended, creating new opportunities and enabling new DfAM strategies. For example, part orientation, once chosen, is fixed in most AM processes. However, the possibility to change the part orientation in-process does exist for some AM families. Increasing the orientation degrees of freedom in space and time increases the possibilities for controlling and therefore optimizing orientation-specific qualities such as surface roughness and material properties. Similarly, it increases the probability of being able to specify a build order of operations that will result in a self-supporting structure and therefore eliminate the need for supports.

Bi-direction deposition enables the exploitation of symmetry in the deposited volume. For example, the build plate can be placed along a line of symmetry in the part (Fig. 3 and Fig. 44) or two parts can be built back-to-back (Fig. 45). If thermal-based processes deposit alternate layers in opposite directions, the two halves will have identical but opposite residual stress states [352], balancing the component stress and reducing or eliminating distortion. This is straightforward when the substrate divides the part in two equal volumes; otherwise redesign of the part might be required. If parts are built back-to-back, the cost and waste associated with buying, preparing, and removing the sacrificial built plate is reduced.

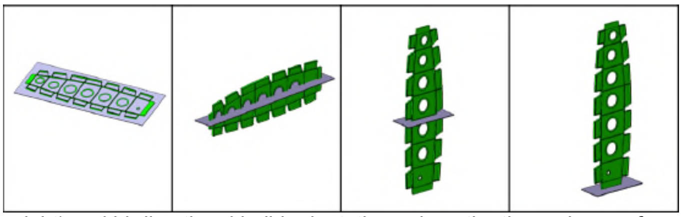

Fig. 44.Examples of unidirectional (far right) and bi-directional build orientations along the three planes of symmetry for a wing rib. Based on [116]. Images courtesy of the Welding Engineering and Laser Processing Centre at Cranfield University.

Fig. 45.Ti–6Al–4V wing spars (1.2m long) built back-to-back on a sacrificial build plate for BAE Systems [352]: side view show one wing spar (left) and top view showing both wing spars (right).

Multi-directional deposition can be adopted to minimise non-value-adding time. For example, WAAM deposition must be performed on underlying material at a fixed temperature to consistent deposition conditions. This can result in long machine idle times during cooling. However, if a layer can cool while another is being deposited on the opposite side, the only non-value-adding activity is the part rotation. Finally, layers can be deposited out-of-position [165]. For example, two deposition heads can work simultaneously on opposite sides of a vertical starting plate. This doubles the deposition rate and still results in zero distortion. It does not help heat management because the two volumes are being deposited at the same time, but this might not be an issue for large (multi-metre) parts. These considerations should be taken into account when defining the design and production strategy. Otherwise, they may result in costly redesign later in the product development process.

5.2.4 Discussion

These issues are tightly coupled. It is rarely possible to simultaneously optimize the part orientation to reduce material usage and production cost, improve surface and overall build quality, control the material properties, and eliminate the need for support. To balance these considerations, researchers have used genetic algorithms [54][60][205][257], swarm intelligence [127], multi-objective optimization [82][245], and multi-attribute decision making processes [368][369][371][372] to identify the most optimal orientation for a given part. In addition, discretization and directionality are strongly tied to the characteristics of the AM process and the capabilities of the specific machine used. Thus, build orientation and support strategies cannot be developed independently from the process, machine, and process parameters.

5.3 Constraints due to process characteristics and machine capabilities

Every additively manufactured part is affected by the characteristics of its process family and the capabilities of the specific machine(s) used. Process specific characteristics include the material deposition method, the recoating method (if any), and the bonding principle. These determine the types (polymer, metal, etc.) and nature (e.g. powder shape and size) of raw materials that can be processed; the resulting material properties and characteristics; the anchoring and support requirements, options, and strategies; if material can become entrapped in internal voids and blind holes; and what postprocessing procedures can or must be performed. These are constant for all machines of a given type and are different for each class of AM process listed in Fig. 2. Machine specific capabilities and requirements include the input and data file requirements and options; the minimum build resolution (usually in x, y, and z) and the other resolutions that can be chosen; the maximum build dimensions (usually in x, y, and z); the available and compatible materials that can be used; the process parameters that can be varied and the options for varying them; and the postprocessing parameters that can be varied and the options for varying them. These are rarely fundamental limitations and can often be overcome by buying or building a different machine.

Together, the process specific characteristics, the machine specific constraints, the choice of material(s), and in some cases the support strategy place limitations on the parts that can be built and define the qualities and characteristics of the parts. For example, they determine the warpage, shrinkage, accuracy and precision of the part; the dimensional stability of the part; the surface roughness of the part in x, y, and z; the minimum feature size in x, y, and z; the minimum spacing between features; the maximum aspect ratio of a feature; and the unsupported and supported feature shapes and sizes that can be produced. Given these constraints, designers must choose an AM process that can produce the specified part in the specified material with the required quality, choose a non-AM process or combination of AM and traditional processes that have the required capabilities, or modify the design and its production strategy to compensate for the constraints that are imposed by AM.

5.3.1 AM design guides for general material and process specific considerations and constraints

A number of AM design guides have been published to outline process and machine specific constraints and considerations. For example, Materialise published 19 design guides for a variety of materials [207]. Each guide provides a set of 'design specifications' that include minimum wall thickness, minimum detail size, expected accuracy, maximum part size, clearance, and if interlocking or enclosed parts are possible. These are followed by a set of 'basic rules, tips, and tricks' that are material and process specific. Stratasys published three guides that address DMLS [296], FDM [300], and laser sintering [304]. These are also process-specific with little overlap in content. Shapeways has published design guidelines for 16 materials [286]. Each guide includes the minimum and maximum bounding box, minimum supported and unsupported wall thickness and wire size, minimum embossed and engraved detail, minimum escape hole for entrapped material, if enclosed and interlocking parts are possible, if multiple parts per file is possible, the expected accuracy, and the expected look and feel of material. Additional material specific information such as design tips and information about handling and care of the final parts is also included. Finally, 3D systems published two design guides that focus on application specific considerations for brass [3] and plastic [5] SLS components that include features such as internal channels, cages, assemblies, interlocking / woven parts, springs, hinges, snap fits, and threads.

In the academic literature, Adam and Zimmer [10] presented a catalogue of design rules for laser sintering, laser melting, and FDM that address geometric constraints such as sharp edges, element transitions, unsupported features, and feature spacing. Additional process-specific design rules have been proposed for FDM [322], SLM [325], EBM [336] and WAAM [220][221][222].

5.3.2 AM benchmarks for material and machine specific considerations and constraints

While design rules and guidelines can provide a useful starting point, they do not provide information about individual machines and local capabilities. When more detailed information is needed to support design, benchmarks can be used to study and compare AM processes, parameters, and production strategies. Early AM benchmarks were used for process optimization, comparison, and selection. They were relatively large and contained features that were easily characterized by CMMs [53][238][239]. Over time AM benchmarks gained more 'real' features (holes, bosses, towers, angles, notches, thin walls, fine features, freeform structures, etc. [238]) that could be used to develop local rules for DfAM (Fig. 46). Benchmarks have also become more specific over time, focusing on design considerations such as surface roughness (Fig. 38), overhangs and support structures (Fig. 47), and cellular materials (Fig. 48). Finally, benchmarks, such as Proto Labs' torus design aid [265], are starting to be offered by AM service providers.

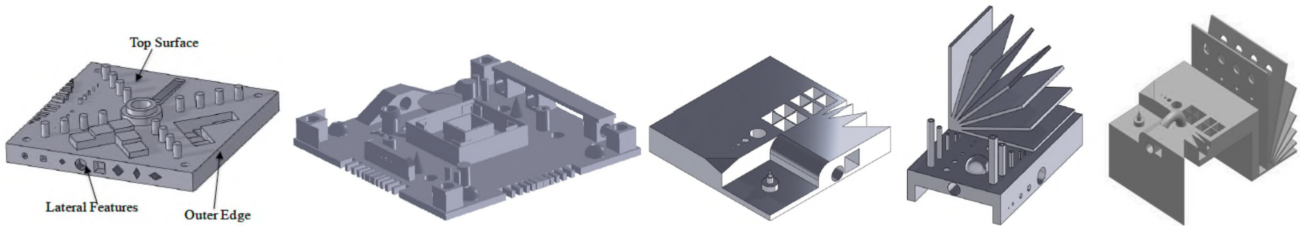

Fig. 46.AM benchmarks with design related features from [239] (top left), [196] (top right), [180] (bottom left), [63] (bottom center), and [363] (bottom right). Adapted from [239] and [363].

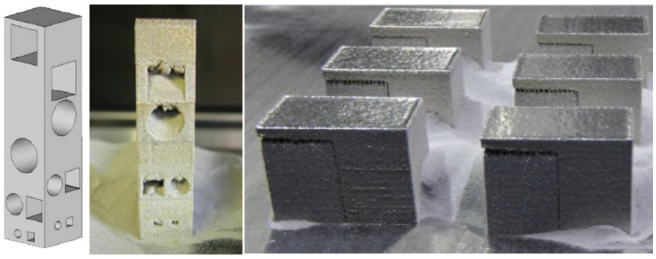

Fig. 47.Test parts to investigate the design of overhangs (left, [225] adapted from [264]) and support structures (right, [264]).

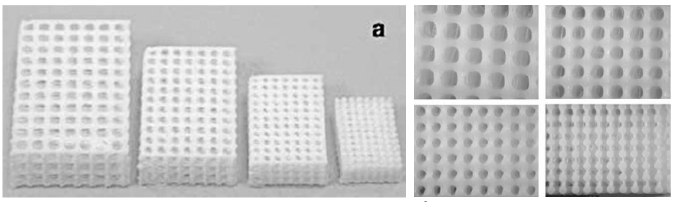

Fig. 48.Benchmarks to investigate the design of FDM porous structures [24].

5.4 Constraints associated with material properties and processing

In many cases, raw materials can be used in AM processes without modification. However, some materials must be adapted before they can be used. For example, laser sintering gold requires a change in the alloy to prevent the raw material from evaporating [104]. Similarly, the proportion of ingredients in additively manufactured food affects properties such as dimensional stability [192], requiring some recipes to be optimized for AM. In addition, AM processing can change the material properties of the final parts. Although this was presented as a design freedom in section 4.2.1, it is also a design constraint. For example, Ti-6Al-4V ELI parts produced using DMLS have a higher tensile strength and a lower breaking elongation than the bulk material. This is undesirable when producing medical implants. A common countermeasure is to use postprocessing treatments to achieve the desired mechanical properties. For example, post heat treating Ti-6Al-4V ELI at 800 °C for 2h leads to a significantly improved fracture elongation compared to the as-built condition [109] (Table 1). Finally, the material properties can be influenced by the proportion of recycled raw material used and by the recycling process. Thus the cost and waste associated with AM must be weighed against any potential degradation in quality.

Table 1. Mechanical properties of Ti6Al4V ELI used for medical implants: requirements according ASTM F136 for conventional and ASTM F3001 for AM bulk material compared to the typical mechanical properties of DMLS processed sampled in the conditions as-built and heat treated [109].

	Bulk material ASTM F 136	AM bulk material ASTM F 3001-14	Typical DMLS as-built (XY build direction)	Typical DMLS heat treated (XY build direction)
Tensile strength [N/mm²]	Min. 860	Min. 860	1260 ±40	1075 ±30
Yield strength [N/mm²]	Min. 795	Min. 795	1125 ±65	1000 ±40
Breaking elongation [%]	Min. 10	Min. 10	7 ± 3	13 ± 3

5.5 Constraints associated with metrology and quality control

While the unique capabilities of AM present great opportunities at the beginning of the design process, they create major challenges for metrology and quality control after production. These challenges are related to the verification of materials, geometries, and surfaces. Because AM creates the part material and geometry at the same time, AM parts must be inspected for defects in the bulk material including undesirable grain characteristics, unexpected porosity, and larger internal voids. The challenge increases dramatically for functionally graded materials. In addition, AM materials cannot be assumed to have the same properties as their bulk counterparts. Thus, characterization techniques for the mechanical or optical properties of the material may need to be adjusted before they can be used.

The organic, freeform external geometries that can be created by AM require more complex measurement techniques and greater data processing capabilities. The first (and perhaps most important) challenge is the mere fact that current specifications systems as defined in ISO [154] were not developed for complex freeform shapes. In addition, it is not straightforward to assign a "tolerance zone" to a freeform shape and connect this to its function and manufacturability. There has been some research related to communicating requirements for [175] and estimating form errors of [64] freeform geometries in optics. However, little or not work has been done in this area for AM. The verification of critical internal features, such as conformal cooling channels, is even more challenging [339] and will require improvements in non-destructive imaging technologies such as ultrasound and computed tomography. The difficulty and importance of verifying internal geometries increases substantially when considering multi-scale cellular and lattice-based structures and materials [334][360]. Here the challenge lies both in imaging these bodies and in interpreting the results using advanced methods as described in [161].

Designers must keep in mind that the early choices they make in the design process will have a major impact on the downstream requirements for production and quality control. Thus, designing for metrology and quality control must be a part of DfAM.

5.6 Through life constraints: maintenance, repair, and recycling

Sections 4.3.2 and 4.3.3 presented embedded components and printed assemblies as benefits. However, as-printed assemblies usually cannot be disassembled for routine maintenance or repair [59]. If part of an assembly breaks and it cannot be disassembled and reassembled, then the whole assembly has to be replaced. This increases the cost and the waste associated with the product throughout its usable life. This is especially important because with few exceptions [115][226], relatively little work is being done on determining and improving the wear properties of AM parts. The problem increases for objects with embedded components and multi-material assemblies because they are also difficult to disassemble for recycling and disposal. Design strategies to address and overcome these limitations must be developed in the future.

5.7 External and regulatory constraints

The many benefits of AM described in section 4 led to widespread interest and early adoption of AM for end use parts in the aerospace and medical industries. However, both industries are highly regulated and require parts to gain regulatory approval before being put into use. Thus, the designer and the design are constrained by the need for testing and documentation to support the certification and approval process. Obtaining regulatory approval can be challenging since AM processes are relatively new and do not have the same historical data that is available for conventional processes. In addition, AM machines have a higher inherent variability than is seen in more mature technologies. As a result, in aerospace AM is currently being used mainly for non-safety-critical parts and mostly on military rather than commercial aircraft [58]. More recently, some aerospace manufacturers have commented on the wider use of AM parts [244]. To gain regulatory approval for these, the consistency of the AM process itself must be proven and stringent materials safety testing must be performed.

Most medical applications of AM have been for medical models and removable prosthetics [58]. Where implants have been used, it has often been on a 'single-use, experimental' basis where explicit permission is obtained from a specific patient. However, there are some notable exceptions such as the large-scale production of hip implants. The manufacturers of such implants must also demonstrate consistency of both process and material to gain regulatory approval.

6. Costs and benefits of AM products and processes

The cost of AM is often viewed as one of the biggest barriers to adoption in industry. However, there are many examples where the value added by AM far outweighs the costs. This section explores the costs and economic benefits of AM-based production as barriers, motivations, and considerations for DfAM. It presents some of the major cost models that have been developed for AM, considers the requirements for successful AM business models, and presents a series of case studies that explore the economic viability of DfAM.

6.1 Costs of AM parts and production

AM costs are usually divided into well-structured direct production costs (e.g. labor, material, and machine costs) and ill-structured costs (related to build failures, transportation, inventory, etc.) [326][354]. Traditional cost models focused on the well-structured costs and were intended to compare AM processes to each other or traditional manufacturing processes and to identify strategies for process and product cost optimization. More recent work has discussed the need for [190] and attempted to [170] evaluate the costs and economic benefits of AM by considering all life cycle costs.

6.1.1 Cost models for AM production

Hopkinson and Dickens [148] proposed one of the earliest generic AM cost models. This model assumes that one product will be produced on the same machine for the entire economic lifespan of the machine. It includes machine costs (purchase, depreciation, and maintenance), labour costs (operator, setup and post processing), and material costs (direct material costs and material cost for support structures). The model was used to compare the direct printing cost of two plastic parts produced by SL, FDM, laser sintering (LS), and injection molding. It indicated that the cost per AM part was driven by the production speed and the break-even point between LS and injection molding was driven by part size. It was estimated that LS was economical up to 14,000 pieces for the smaller part (Fig. 50) and up to 700 pieces for the larger part.

Ruffo et al. [275][276][277][278] expanded upon that work to create a more flexible and realistic cost model that included different parts in a single build; indirect costs such as administrative costs, part design and production overhead; and the cost of powder material reuse and waste. While Hopkinson and Dickens predicted a price per product that was independent of production numbers, Ruffo et al. found that the price per parts drops as the costs of part design are distributed over more products and when adding more parts to the same production layer. It jumps up again when new layers/builds are used (Fig. 49). This results in a higher and more plausible cost for lower production volumes and predicts higher costs for higher production volumes [277]. As a result, Ruffo et al. predict a lower break-even point between LS and injection moulding for the smaller part from [148] (9000 vs. 14,000 pieces).

More recently, Atzeni and Salmi [29] developed a model to estimate the cost of DMLS metal parts. It included machine costs (including interest and maintenance over a 5 year usable life), material costs (volume multiplied by 1.1 to compensate for support and waste), and pre-, and postprocessing costs as labor. The model was used to compare the cost of a 1:5 model of an aluminium airplane landing gear assembly (overall dimensions 70×210×70mm; mass 0.18kg) produced using DMLS and High Pressure Die Casting (HDPC). They estimated the cost of a single DMLS assembly to be 526.31 EUR (material cost 5%, pre-processing cost 1%, build costs 90%, post processing cost 4%) vs. 21.29 + 21,000/N EUR for HDPC. This results in a break-even point of 42 parts.

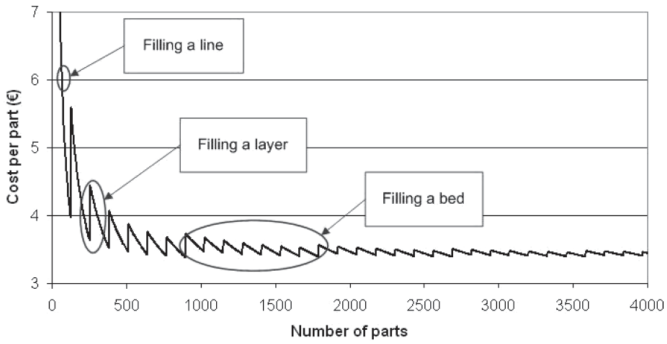

Fig. 49.Cost per part vs. the number of parts produced estimated using the model from [276] applied to the lever from [148].

Many variations of these cost models exist in the literature. Li [188] included labor costs for pre- and postprocessing, material costs (part volume/0.7 to account for support and material waste), machine cost per hour (purchase cost over annual utilisation and years until return), and overhead (rent, electricity, etc.). Allen [15] considered labor, material costs (part volume, raw material costs, and material usage efficiency), capital (machine) costs, power costs (including power conversion efficiency and power delivered to the part), the build rate, and the cost of consumables. Grimm [133] considered pre-, printing, and postprocessing time; capital costs (machines, facilities, etc.); annual operating costs (service, maintenance, consumables, material disposal, etc.); and hourly costs (assuming a 60% utilization rate). Baumers [37] considered total indirect cost per machine hour (machine costs, overhead, labor, utilisation rates, and usable equipment lives), material cost, and electricity costs. Gibson et al. [130] included labor costs (including setting up the build, postprocessing, and cleaning and resetting the machine), machine purchase cost (allocated based on the part build time and machine usable life), machine operation costs (including maintenance, utilities, floor space, overhead, etc.), and material costs (based on part volume, multiplied by up to 1.5 to account for support and multiplied by up to 7 to account for material waste). Lindemann et al. [190][191] built on the work of Gibson et al. with an extensive model to define machine costs. They also introduced a part complexity factor to allow for the increased time needed to design support structures and place complex parts in the build environment. Rickenbacher et al. [269] developed one of the most comprehensive models to date. Their model includes detailed cost estimates based on the full SLM process chain and is suitable for jobs with different parts sizes, complexities and quantities. For a full review of AM cost models to date, see [326].

6.1.2 Machine costs for AM production

The cost of hardware is a major contributor to the total cost of AM products. Hardware costs are defined mainly by the capital equipment costs, service and maintenance costs, build time, and machine utilization. Table 2 shows the relative contribution of AM machine cost to the total product cost for FDM, SL, and SLS for a plastic hinge (Fig. 50) from 2003 [148] and for EBM and DMLS build plates with a variety of parts (Fig. 51) from 2016 [38]. For the polymer processes, the contribution of hardware to the total part cost ranged from 24-75%. SLS had a higher annual production volume than FDM and SL and therefore the lowest cost per product and the lowest relative contribution of the hardware to the cost. The SL hardware had the highest contribution to the cost of the final product (75%) because of (8x) higher hardware procurement costs. For the metal processes, the estimated relative contribution of hardware was in the range of 40-55%. The EBM and DMLS machines had comparable procurement costs. The differences in the relative cost contribution of the hardware to the total volumetric cost (3.26 €/cm^3 for EBM and 8.41 €/cm^3 for DMLS) stem from differences in layer height (deposition rate), preheating and cooling, and postprocessing.

6.1.3 Build time models for AM production

Build time dictates how machine costs are allocated to a given part and is therefore essential for accurate AM cost estimations [87]. Existing build time models can be grouped into 3 categories: models dedicated to one process using a limit set of parameters; generic build time models that use many parameters to estimate build times; and parametric models that use neural networks to predict production times based on historic data. For example, Ruffo et al. [275] modelled build time as a black box: part dimensions, volume, powder bed volume and bounding box volume went in and a build time came out. The relationships between the inputs and outputs were determined empirically. This approach requires very few input variables to obtain a good estimate of build time (generally conservative and within 12% of the actual build time), however only one type of machine was used and the settings were kept constant. Thus, the method is transferrable but the results are not. Byun and Lee [54] proposed a generic build time model assuming that build time is “proportional to the sum of the idle time between layers (except for the curing, sintering or deposition operation), the time taken to fabricate a part, and the time taken to generate the supports”. Gibson et al. [130] used a similar approach, assuming that build time is equal to the scan (or deposition) time plus the recoat time between layers and the delay time. More recently, process-specific built time models have been proposed for SLM [269], SLS [367], and FDM [373]. Finally, di Angelo and di Stefano developed a neural network-based build time estimator [87]. After 72 training cases, they were able to estimate the build time of six different FDM samples with errors ranging from 6.07 to 20.3%. For a full review of AM build time models to date, see [326].

Table 2. Relative contribution of AM machine procurement cost to total product cost for FDM, SL, SLS [148], EBM, and DMLS [38]. A factor of 1.3 was used to convert £ to € for the EBM and DMLS parts.

	Polymers (2003)			Metal (2016)	
	FDM	SL	LS	EBM	DMLS
Annual AM machine costs (k€)	23	219	73	57	59
AM machine cost per product / build (€)	2.64	3.92	0.52	513	1964
Total cost per product / build (€)	4.47	5.25	2.20	1246	4183
Relative AM machine cost per product/build (%)	59	75	24	41	47

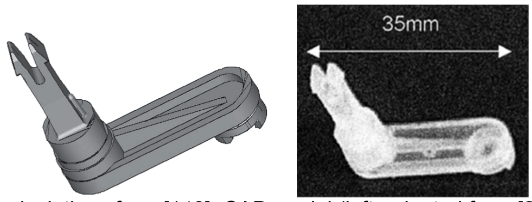

Fig. 50.The plastic hinge used in calculations from [148]: CAD model (left, adapted from [276]) and printed part (right, [148])

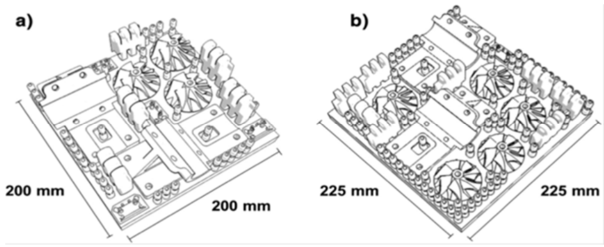

Fig. 51.The build platform and printed parts used for the cost calculations in [38]: EBM layout (left, a) and DMLS layout (right, b).

6.1.4 Material costs

AM materials have relatively high procurement costs. Today, thermoplastic and photopolymer materials for AM cost $175-250 per kg. This makes AM materials 58 to 125 times more expensive than the raw materials for injection moulding [355]. More specialized thermoplastic materials cost up to 500 $/kg while PLA and ABS filament for at-home printers sell for 15-50 $/kg. Metal powders have a price range of 78-120 $/kg for stainless steel and up to 340-880 $/kg for titanium (alloys) [354]. Wire feedstock is normally one order of magnitude cheaper than powder. Material costs depend on the source. Large variations have been observed in the cost of metal powders when bought from a system manufacturer or purchased directly from a metal spraying company.

AM processes also have high relative contributions of material costs to final costs. For example, the contribution of the material cost to the final cost of an aluminium part can be 9.9 times greater when using AM instead of a traditional process [29]. The contribution of the material costs to the final product in metal powder-based AM product can vary from 11% and 46% [326].

6.1.5 Labour Costs

Low labor intensity is thought to be one of the key benefits of AM. However, the pre- and postprocessing stages often involve manual activities such as file repair, support structure design, build chamber layout, cleaning, support removal, sintering or heat-treating, and surface finishing. The impact of these costs on the product price can be considerable, especially for low production volumes (Fig. 49). Most cost models assume higher production volumes for a single design and therefore underestimate the labor costs of AM products.

6.1.6 Energy consumption

Although the energy consumption of the AM processes is important from life cycle and sustainability perspectives [167], it plays a minor role in cost comparisons today. For example, it was estimated that energy costs in [148] and [38] contributed less than 2% of the total part cost. For a detailed analysis of energy and resource efficiency in SLM and SLS, see [167]. For a discussion and review of the AM energy consumption literature, see [326][354].

6.2 Business cases for Design for Additive Manufacturing

Competitive businesses cases can be made for Additive Manufacturing when it adds sufficient value to a product to justify higher production costs, reduces product development costs, reduces production costs, reduces costs over the entire value chain, reduces the cradle to grave costs of the product, or provides some combination of these benefits. AM can be used to increase the economic, ecological and experience values of products [59]. Other values such as the freedom to produce parts in-house (eliminating the risks due to dependence on external suppliers and reducing supply chain vulnerability) [278], protecting business secrets, and preventing piracy [159] are difficult to quantify but nevertheless contribute to profitability. The 'tool-less' nature of AM allows it to reduce direct production costs when complexity and/or customization are high and when volumes are low [76]. It can also shorten lead times compared to conventional methods. As a result, AM can lead to an overall reduction in time to market and time to profit.

Deradjat and Minshall [86] observed that business case for DfAM can be based on benefits from any part of the AM business framework: technology, operations, organizations, and external influences. For example, improvements in operations, organizations, and external factors, especially in terms of over production and in the areas of supply chain and inventory control, can enable lean, agile, or Just-In-Time manufacturing [76][147][224][283][331][326] and increase profitability. This increases the scope of DfAM from the design of the product to the design of the production system. The potential for AM in the supply chain has been investigated in the aerospace industry [230], in the shipping industry [344], and by the air force [170] and navy [144]. These studies concluded that the benefits of AM in the supply chain are not yet being realized in these areas. However, industrial case studies in the medical and dental industries show that these benefits are being realized today. For example, customers' dental models are being stored as digital files instead of as physical parts, lowering costs and providing better protection of the information [293][297]. Acist Medical Systems reports that their inventory also takes the form of digital files on a server. If a part breaks, the company prints a replacement and ships it the next day [297]. And, ScriptPro is using AM to produce bezels for their vial handling systems. Since they don't know which bezel will be needed for which machine and vial type until it is ordered, FDM is used to produce the parts on demand in house [312].

Finally, maximizing the business benefits of AM requires a through-life approach that considers production, use, maintenance, repair, and disposal. For example, AM is currently being used to repair gas turbine blades [106][176]. It is also being used to produce on demand parts for emergency repairs. For example, a recent case study showed that printing a component for an emergency repair of a labelling system saved Anheuser-Busch "nearly 70% in production costs alone" because of the quick delivery time [313].

6.3 Successful examples of AM products in industry

This section presents six examples from industry where AM added value, improved functionality, and reduced time, cost, and waste.

6.3.1 On demand workpieces to reduce lead time, cost, and waste

Using AM to produce near net shape workpieces can substantially reduce lead time, cost, and material waste. This is especially important for the aerospace industry where many components require substantial material removal; are slow, difficult or expensive to machine; and have high material costs [15]. Fig. 52 shows a custom 2.5mm thick truncated cone that was printed using WAAM and then welded to a commercially available flange. The printed workpiece can be produced in a few hours. Purchasing the same workpiece made using conventional methods would cost almost ten times more and take up to 6 months to receive. The buy-to-fly ratio (in this case, the material purchased and used compared to material specified in the final CAD files) for the printed cone was 1.25. In comparison, aerospace parts machined from forged billets often have buy-to-fly ratios in the range of 6 to 20 [15][352] and can be as high as 40 [352]. [204] compares the cost of products with buy-to-fly ratios between 6 and 37. Direct cost savings of up to 69% were found for WAAM compared to milling the same parts from stock.

Fig. 52.Truncated cone produced in mild steel by Wire + Arc Additive Manufacturing: as printed (left, courtesy of the Welding Engineering and Laser Processing Centre at Cranfield University) and welded (right, [352]).

6.3.2 Reduced part count, mass reduction, and increased usable life

GE aviation redesigned the fuel nozzle for its new LEAP engines for DMLS (Fig. 53, left). The redesigned nozzle reduces the number of brazes and welds from 25 to 5. It also increases the lifetime of the fuel nozzle by a factor of 5 and reduces the mass by 25%. Production rates of up to 40,000/year are expected [124][184].

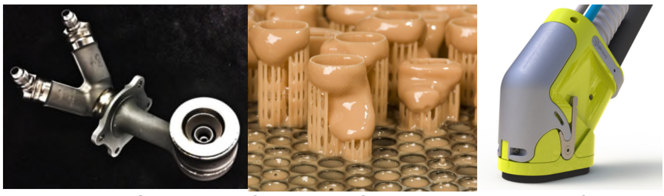

Fig. 53.Commercially successful AM products: GE Aviation fuel nozzle for the LEAP engine (left, [124]) and hearing aids produced by vat polymerization (center, [117]), and casing of the handheld Piblaster of Pinovo as produced by Materialise (right, [211]).

6.3.3 Reduced production costs of customized hearing aids

Historically, personalized hearing aids (Fig. 53, center) were produced by investment casting using a wax model of the inner ear. This is being replaced by 3D scanning the wax model followed by AM. This substantially reduces production costs. It is estimated that more than 10,000,000 AM hearing aids are in circulation today [117].

6.3.4 Improved safety and functionality and reduced waste

Pinovo designed a handheld pipe blaster (Fig. 53, right) with housing shape and material requirements that could not be achieved with injection moulding. Instead, the housing was produced using laser sintering of alumide. The new design reduced waste production by 75-90%, increased operator safety, and improved flexibility in responding to customer demands [211].

6.3.5 Reduced costs and lead time for an electrical enclosure

ASML redesigned an electrical enclosure for AM (Fig. 54). The original enclosure was composed of 3 brazed parts and required a total of 34 steps in the process chain: 11 machining and joining steps, 7 material treatment and cleaning steps, 8 quality checks, and 8 packaging and transport steps. The overall lead-time was 21 weeks. The part was redesigned for AM to optimize process flow and cost. The redesigned part requires a total of 11 process steps: DMLS followed by annealing, 3 machining and joining, 2 material treatment and cleaning, 2 quality checks, and 2 packaging and transport steps. This reduced the lead-time by 70% and reduced costs by 20%.

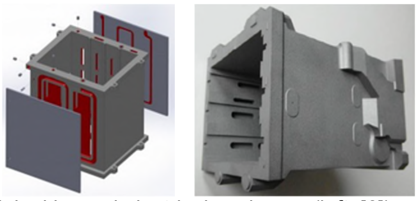

Fig. 54.Exploded view of the solid model for the original brazed electrical enclosure (left, [6]) and the final printed part (right, courtesy of ASML).

6.3.6 Weight reduction, functional optimization, and improved robustness in the semiconductor industry

ASML also redesigned a manifold for AM. The original design was composed of PEEK bodies connected by polyurethane hoses. They created two alternative designs: a monolithic milled design that replaced the hoses with solid channels sealed by welded cover plates and a design that was optimized for production by SLM (Fig. 55). A detailed cost breakdown of the three designs in shown in Table 3. Redesigning for AM had benefits for both the product and the process. The AM variation could be optimized for flow and therefore had improved dynamic system performance. The AM variable was more robust and almost 10% lighter than the original. Using AM eliminated the welding and assembly steps. It also reduced the amount and cost of machining necessary and reduced the cleaning and other post treatments needed. However, in this example, the AM variation is still too costly. To make the AM part economically viable in production, it is estimated that the direct AM costs must be reduced by 50% (by increasing build speed), machining costs must be reduced by 25% (by improving the accuracy and quality of the SLM process), and the overhead must be reduced by 20% for a final part that is no more than 120% of the cost of the conventional design.

7. Summary, conclusions, coming trends, and future work

This paper has presented some of the major design opportunities, constraints, and costs associated with DfAM and demonstrated some of what is possible and affordable today. However, Design for Additive Manufacturing is still in its infancy. There is insufficient understanding of when and how to design for AM and many of the technologies needed to support it are not yet mature. This section explores some of the future challenges and coming trends that will shape DfAM and the technology it will enable.

7.1 Guidelines for when and how to Design for AM

Although AM can be “an economically convenient alternative to conventional manufacturing processes” [30], it is agreed that parts should be redesigned for AM and not simply reproduced using an AM process [30][130][191][270]. Lindemann et al. [191] presented a method to select candidates for AM from a larger pool of parts. The 2015 draft of ISO ASTM/DIS 20195 [157] also includes a procedure for identifying the potential of AM for a given part. However, much more work is needed to understand what kind and how much redesign is necessary or optimal for a given situation, how to modify the design process and the design strategy to maximize the benefit, and to develop software to support this work.

One promising (re)design strategy is to take a functional surface approach [142][261][335][370] and design parts from the bottom up. Fig. 56 shows the top down design of the monolithic manifold from Fig. 55, starting with the maximum envelope and then removing material to create the functional features and reduce mass. Fig. 57 shows a bottom up functional surface approach, starting with the interfaces, defining the maximum envelope constraint, and then adding the functional features and structural reinforcement. While the functional surface approach results in a design that is half the mass of its top down counterpart, it requires geometric modelling capabilities that are not yet common in commercial CAD packages. Functional surface design approaches also require a closer link between design and analysis. Thus, the multi-physics capabilities that were once limited to high-end finite element programs may soon be needed in most major commercial CAD packages.

To receive the full benefits of AM, designers must learn to think differently while focusing on creating robust industrial solutions with added value. Design theories, processes, methods, tools, and techniques [194] must be adapted or developed to address the inherent coupling between material, geometry, and quality in these systems. Specialized and application-specific tools must be developed to support the design of cellular structures, meta materials, heterogeneous artifacts, and biological scaffolds (e.g. [259]), and more. Finally, it must be acknowledged that each build is a design artifact with its own requirements and constraints, and its own features (e.g. support structures, part layout, etc.) to be designed and optimized. Thus DfAM must extend beyond the product to the production system and consider the entire value chain.

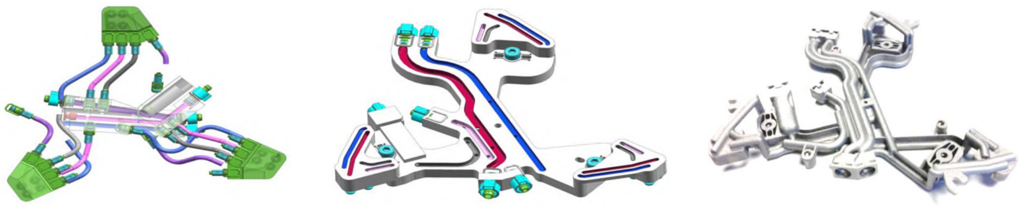

Fig. 55.Three designs of a manifold from the semiconductor industry: conventional design made of PEEK with hoses (110g) (left), monolithic design milled in TiGr5 (200g) (center), and optimized design printed in TiGr5 using SLM (100g) (right). Courtesy of ASML.

Table 3. Cost breakdown of the three manifold designs shown in Fig. 55 as a percentage of the total cost of the conventional design. Courtesy of ASML.

Concept	Material & standard parts	AM cost	Machining cost	Welding / assembly cost	Treatments / Cleaning / Quality	Overhead / risk / profit	Total cost
PEEK & hoses	15%		33%	21%	8%	21%	100%
TiGr5 milled	1%		59%	54%	4%	38%	156%
TiGr5 SLM	4%	113%	28%		3%	35%	185%

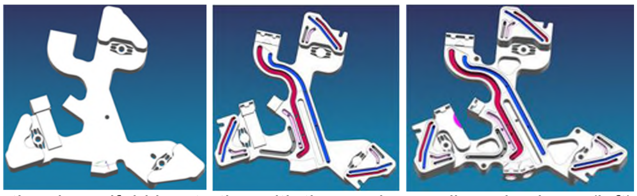

Fig. 56.Top down design of a conventional manifold by starting with the maximum allowed volume (left), removing material for the functional surfaces (center) and then reducing mass (right). Courtesy of ASML.

Fig. 57.Manifold designed from the bottom up for AM starting with the interfaces (left), defining the maximum envelope as a constraint (center), and then adding functional features and reinforcement (right). Courtesy of ASML.

7.2 Redefining the roles of the designer and manufacturer

AM will continue to redefine the roles and relationships of the designer and the manufacturer, making it easier to merge them into one individual and location (enabling home production and supporting small businesses) and to distribute them over many individuals and locations for truly global product development [89]. For example, GE Aviation has experimented with crowd sourced redesign of an aircraft engine bracket for weight reduction [62]. The contest received 700 entries (Fig. 58) and was so successful that GE is considering another 40 crowdsourcing challenges in the future. Similarly, online repositories of AM artifacts, such as Thingiverse, Fabbaloo, Bld3r, Yeggi, Repables, and Youimagine, make it possible for individuals to produce a wide range of artifacts without needing to design them.

Fig. 58.Examples of crowdsourced redesigned aerospace engine brackets [62]

7.3 Improved quality and consistency and increased standardization

AM process quality, consistency, and capabilities will continue to improve. Existing standards will be applied more to AM. AM-specific standards will become more relevant and complete. And, new AM-specific standards will be developed. These trends are reflected in the literature. For example, Lieneke et al. [189] recently classified the achievable tolerances of several AM processes according to ISO 286-1 taking into account part orientation [153] (Fig. 59). Similar work has been done by Griesbach [132] for SLA, material jetting, material extrusion, and SLS, and by Mintetol et al. [227] for FDM. Such efforts will enable standards organizations to bring researchers and industry together to establish standards that can be built upon to support process-specific DfAM, more general process selection, and process chain development.

7.4 New manufacturing paradigms and a divergence of manufacturing system complexity

AM process chains will become simpler as postprocessing needs are reduced. They will also become more complex as AM technologies are better integrated into the production environment. More hybrid AM processes will emerge and more commercial hybrid AM machines will become available. AM processes with more degrees of freedom will be developed. And, automation of AM, especially for postprocessing and part transfer between machines, will increase. This will lead to an increase in sensors and information processing capabilities in AM production systems. Eventually, most production scale AM will be done with cyber-physical manufacturing systems. The direct digital nature of AM combined with the use of cyber-physical systems will allow for cloud-based AM [186]. The benefits of cloud-based approaches have already been demonstrated in process optimization [320], adaptive process planning [235], shop-floor planning [234], scheduling [236], and maintenance [237]. The benefits of higher quality, hybrid, high DOF, cyber-physical, and cloud-based AM systems are expected to be emergent. To take advantage of these benefits, new classes of design tools [194], rules, strategies, and production planning techniques will be required beyond what is needed today.

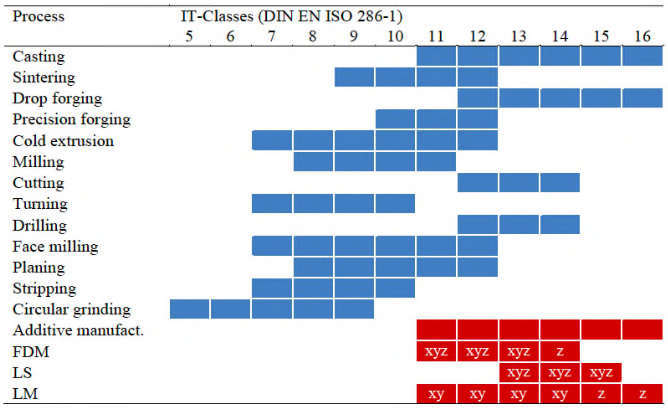

Fig. 59.Achievable tolerances of select traditional and AM processes [189]

7.5 Design education

Finally, all of the developments in tools, rules, theories, methods, processes, and planning must be compiled and made available to support design activities and training in educational institutions and in industry. Design, as a field of study and practice, will have to be adapted to AM processes. Design representation, analysis, and optimization tools will have to be transferred from academia and research (and the hobby community) to industry and practice. Thus, the future will bring educational materials related to DfAM at all levels and for all engineering professions.

7.6 Conclusions

Advances in Additive Manufacturing are bringing about new design possibilities, products, and production paradigms. While much work will be required to bring Design for Additive Manufacturing to maturity, businesses, both small and large, are exploring and adopting AM for end use parts in at an astounding rate. Progress is being driven from the top down and the bottom up, from individuals and industry, in research and practice. The results will rewrite the rules of product development and new product introduction. A new era is beginning.

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