Fraunhofer Additive Manufacturing Alliance

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From data straight to highly complex products

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Summary

Additive manufacturing is known as 3D printing in popular science. It refers to a relatively new group of manufacturing techniques with unique properties and possibilities compared with conventional manufacturing technologies. The Fraunhofer Additive Manufacturing Alliance currently coordinates 17 Fraunhofer institutes working on additive manufacturing. It covers the entire process chain: the development, application and implementation of additive manufacturing techniques and processes as well as the relevant materials. This chapter provides an overview of the technologies, applications, particular opportunities and further goals of applied research in the area of additive manufacturing within the Fraunhofer-Gesellschaft. We make particular mention of mesoscopic lightweight design, biomimetic structures, high-performance tools for hot sheet metal forming, ceramic components, printable biomaterial, large-size plastic components, integrating sensory-diagnostic and actuator therapeutic functions into implants, and three-dimensional multimaterial components.

Reimund Neugebauer, *Digital Transformation*
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10.1 Introduction: history of additive manufacturing

Additive manufacturing (AM), often referred to as 3D printing in popular science, is a comparatively new group of manufacturing techniques with unique properties and possibilities compared to conventional manufacturing technologies we know today. During the early days of additive manufacturing in the 1980s, mainly polymers were being processed. Today, however, metals and ceramic are also being used. Until now, the technology for all of the additive manufacturing techniques has been based on a *layer-by-layer build-up of components.* Originally, additive manufacturing techniques were used for quickly producing prototypes and were referred to as such ("rapid prototyping"). Now, however, further development has made the direct manufacturing of serial components and end products ("direct digital manufacturing") possible.

Additive manufacturing techniques are primarily employed for three reasons:

- Individual item and short-run batch production can often be more economically attractive when molds and tools are avoided.
- Fewer manufacturing restrictions (accessibility for tools, demolding ability, etc.) mean that delicate and highly structured components can be produced, e.g. with anisotropic, locally-varying or functionally integrative properties and movable components.
- Personalized solutions (customization) can be implemented where products are tailored to user or application-specific requirements (e.g. prostheses, shoes).

The last two points are the key drivers today, contributing to the increasing spread of additive manufacturing as an alternative production technique. The central challenge here is to master the competition regarding cost and quality of established batch production processes such as machining and injection molding, and to significantly increase process efficiency (energy use, waste generation, and robustness). This is particularly the case where there are high demands in terms of surface quality and component failure on the application side, such as in aerospace and mechanical engineering, and also in the case of large volumes of personalized mass-produced products (mass customization, e.g. of glasses or shoes).

Since 2005 development, and since 2009 market activity have been strongly influenced by two trends: the increasing activities of open source communities (in particular the RepRap project), and the Fab@Home concept (desktop printing such as MakerBot). The fascination with additive manufacturing techniques, the desire to participate in production processes, the opportunity to produce replacement parts on demand, and the reintegration of consumer product manufacturing into local economies are all important drivers of this development. Whereas this development prin-

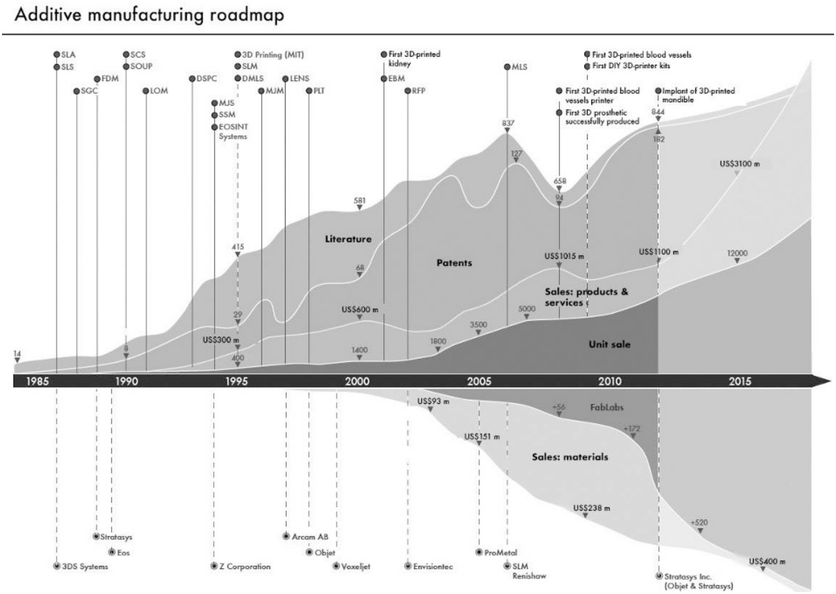

Fig. 10.1 Graphical roadmap of additive manufacturing to the present (Fraunhofer UMSICHT, Fraunhofer Additive Manufacturing Alliance 2012)

cipally addresses additive manufacturing techniques for polymers, metal techniques remain reserved for industrial applications so far. Here, however, unusual innovative dynamism and extraordinary growth rates are to be noted, driven by industrial application sectors such as aerospace, energy engineering, medical technology and tooling/mold and die making. The appeal of additive manufacturing has fundamentally grown over the last three decades. This can be seen from numerous indicators including the frequency of patents and publications, revenue from machines and materials, and the founding of companies and new informal communities (see Fig. 10.1).

The current focus within industrial applications, however, remains largely restricted to metal and plastic materials.

10.2 Additive manufacturing at Fraunhofer

The roots of the Fraunhofer Additive Manufacturing Alliance stretch back to the year 1998 when the Rapid Prototyping Alliance was born. Formally relaunched as the Fraunhofer Additive Manufacturing Alliance in 2008 with eight member insti-

Fig. 10.2 Members of the Fraunhofer Additive Manufacturing Alliance (Fraunhofer Additive Manufacturing Alliance 2017)

tutes, it now comprises 17 (cf. Fig. 10.2) and thus reflects the dynamic global development of this manufacturing technique.

The Fraunhofer Additive Manufacturing Alliance’s comparative global position is measured against various criteria and was assessed as part of a competitor analysis carried out by the Fraunhofer ISI, INT, IAO, and IMW institutes on behalf of Fraunhofer head office [1]. To do this, researchers used first and foremost certain specific indicators to review the appeal of the research field and Fraunhofer’s relative position in comparison to other research bodies. The researchers then used future-oriented studies and publications to assess the long-term potential for applications and research and estimated future market potential and research market dynamics by analyzing patents and publications. They calculated Fraunhofer’s current position compared with other research bodies based in part on Fraunhofer’s patent and publication activities compared with other research institutes. In addition, they carried out a brief survey at the Fraunhofer institutes, which are members of the Additive Manufacturing Alliance or which have been active in publishing in this field. The breadth of the additive manufacturing technologies researched and materials produced here can be seen in Tables 10.1 and 10.2.

Table 10.1 Additive manufacturing techniques in use at Fraunhofer [1]

	Technique/ Institute	**VP**	**MJ**	**PBF**	**SL**	**ME**	**BJ**	**DED**	**Other**
Fraunhofer Additive Manufacturing Alliance	IFAM	x		x		x	x		x
	IKTS	x	x	x		x	x		
	IFF					x	x		x
	IPT							x	x
	IPA	x	x	x		x	x		x
	ILT	x		x				x	
	IWM	(x)^{1}	(x)^{1}	(x)^{1}	(x)^{1}	(x)^{1}	(x)^{1}		(x)^{1}
	IWU			x		x			
	UMSICHT			x		x			
	IGD	(x)^{2}	(x)^{2}	(x)^{2}	(x)^{2}	(x)^{2}	(x)^{2}		(x)^{2}
	IGB	x	x			x			x
	EMI			x		x			
	IST								
	IGCV			x		x	x		
	IAO								
	IWS	x		x	x	x		x	x
	IPK			x				x	
(Previous) publications in AM field but not part of Alliance	ISC	x					x		x
	ICT					x			
	IOF								
	IAP								

(x) R&D contributions only

(x)^{1} Working on the mechanical and tribological characterization of additively manufactured components, the design of components for additive manufacturing and the simulation of process steps.

(x)^{2} Development of algorithms and software for controlling 3D printers (no materials development, but optimization of materials and component properties through adaptation of process parameters)

Legend:
VP – Vat Photopolymerization: selective light curing of a liquid photopolymer in a vat, e.g. stereolithography (SLA/SL)
MJ – Material Jetting: drop-by-drop application of liquid material, e.g. multijet modeling, polyjet modeling
PBF – Powder Bed Fusion: selective melting of regions within a powder bed, e.g. laser sintering (LS), beam-based melting (LBM, EMB), selective mask sintering
SL – Sheet Lamination: successive layering and bonding of thin sheets of material, e.g. layer laminated manufacturing (LLM), laminated object manufacturing (LOM) also: stereolithography (SLA)
ME – Material Extrusion: targeted deposition of material through a nozzle, e.g. fused layer modeling (FLM), fused deposition modeling (FDM)
BJ – Binder Jetting: selective adhesion of powdery material using a liquid binder, e.g. 3D printing (3DP)
DED – Directed Energy Deposition: targeted welding of the material during deposition, e.g. laser powder build-up welding (Laser-Pulver-Auftragschweißen – LPA), direct metal deposition (DMD), laser cladding

Table 10.2 Additive materials in use at Fraunhofer [1]

	Materials/ Institute	**Plastics**	**Metals/ alloys**	**Ceramics**	**Composites**	**Biol. mat.**	**Other**
Fraunhofer Additive Manufacturing Alliance	IFAM		D/A	D	D		
	IKTS		D/A	D/A	D/A		
	IFF	A				A	
	IPT		D/A		A		
	IPA	D/A		D/A	D/A	D/A	D/A
	ILT	D	A	D			
	IWM						
	IWU	D/A	D/A		D	D	
	UMSICHT	D/A			D		
	IGD	D/A[2]	D/A[2]		D/A[2]		
	IGB	D/A			D/A	D/A	D/A Functional nanoparticles (metal oxides)
	EMI	A	D/A		A		
	IST	D/A	D/A		D/A	D/A	Combination process (plastics printing and plasma treatment)
	IGCV	D/A	D/A	D/A	D/A		
	IAO						
	IWS	D/A	D/A	D/A	D/A		
	IPK		D/A	D/A			
(Previous) publications in AM field but not part of Alliance	ISC		A	D/A			
	ICT	D/A		D/A			
	IOF						
	IAP						

Legend

D = Development; A = Application

[2] Development of algorithms and software for controlling 3D printers (no materials development, but optimization of materials and component properties through adaptation of process parameters)

This integrated view and assessment takes account both of the appeal of the technological field of additive manufacturing/the individual technological subthemes as well as of the positioning of Fraunhofer within this field. The following criteria were used to identify Fraunhofer's position (largely defined by the Alliance's member institutes):

- Publically funded projects (Nationally: ranked first by a large margin according to number of projects and total amount; EU: ranked second by total amount, first by number of projects)
- Patent activity (ranked 21st across all additive manufacturing technologies according to analysis of patent family registration between 2009 and 2014; ranked first globally among research institutes; across all technologies among the top 10 research institutes)
- Publication activity (ranked first in Germany and fourth for global scientific publications in peer-reviewed journals; ranked between first and sixth for conference papers, non-peer-reviewed publications and press releases)
- Networking in the scientific community (close networks with players with institutional connections, e.g. professorships of heads of institutes; diverse network with European players in particular, but also with American and select Chinese players but a lack of clear and well-developed network with many players)

On the basis of these assessments, it can be concluded that Fraunhofer is the world's most broadly-positioned research player in the field of additive manufacturing. Its network clearly concentrates on industry companies.

Alongside Fraunhofer's unique position of being active in all of the technology fields, for certain technologies (powder bed fusion, material jetting, and binder jetting) Fraunhofer is among the leading players [1].

The scientific excellence of the Additive Manufacturing Alliance is reflected, along with the aforementioned aspects, in the specialist international Fraunhofer Direct Digital Manufacturing Conference DDMC, organized by the Alliance since 2012, every two years in March, in Berlin. The research findings of the Alliance institutes presented here, the renowned global keynote and specialist speakers, and the large number of conference delegates show Fraunhofer's outstanding worldwide reputation in the field of additive manufacturing.

The Alliance strives to play a leading global role in applied additive manufacturing research. Its focus, then, is on combining the strengths of the Alliance's members and using the various complementary skills to provide an appealing offer of comprehensive commissioned research to industrial customers. The Alliance's research spectrum here stretches right across the entire field of additive manufacturing, in a very comprehensive way, and can essentially be divided into four key areas or research focus areas:

- Engineering (application development)
- Materials (plastics, metals, ceramics)
- Technologies (powder bed, extrusion and printing based)
- Quality (reproducibility, reliability, quality management)

The following selected example projects provide an insight into the diversity of applied research in additive manufacturing (3D printing) at Fraunhofer.

10.3 Additive manufacturing – the revolution of product manufacturing in the digital age

Prof. Dr. Christoph Leyens · Prof. Dr. Frank Brückner · Dr. Elena López · Anne Gärtner
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The AGENT-3D joint research project coordinated by the Fraunhofer Institute for Material and Beam Technology IWS aims to develop solutions to existing scientific and technical, political and legal, and socioeconomic challenges for additive manufacturing together with more than 100 project partners, mostly coming from industry.[1]

Following the completion of the strategy phase and the construction of a measuring and testing center with modern equipment for, among other things, optical and x-ray examination and measurement of additively manufactured components (e.g. using scanners or computer tomography), the consortium is working nowadays on implementing the strategical roadmap by means of basic projects and over 15 technology projects (further technology projects will complete the strategical roadmap until the year 2022). These projectsfocus, for example, on integrating functionalities into components, combining conventional and additive manufacturing, allowing the processing of multimaterials and enhancing the material portfolio for additive processes, and last but not least, quality management along the whole process chain.

Additive manufacturing allows complex components to be constructed layer-by-layer directly based on digital data (cf. Fig. 10.3). The principle of reverse engineering, on the other hand, allows a scaled-up reproduction of an original part

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[1] AGENT-3D, BMBF, *Zwanzig20 – Partnerschaft für Innovation* ("Twenty20 – partnership for innovation") program (BMBF-FKZ 03ZZ0204A)

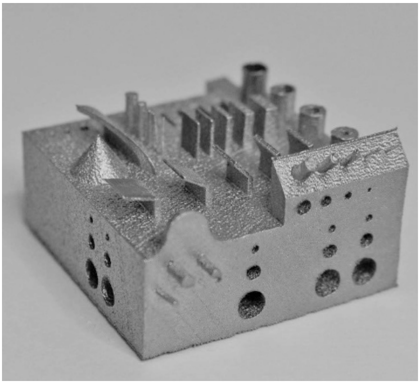

Fig. 10.3 Demonstrator from the AGENT_3D_Basis subproject, manufactured using laser beam melting, to illustrate challenging shapes (Fraunhofer IWS)

Fig. 10.4 Reproduction following scanning of a bird skull in original size and at ten times actual size (Fraunhofer IWS)

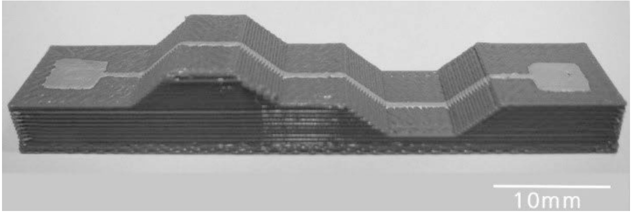

Fig. 10.5 Printed conductor track from the AGENT-3D_elF technology project (Fraunhofer IWS)

Also redesign of the part to fulfill special requirements can be easily done in this way. Scans are used to provide data from which identical or optimized parts in terms of i.e. design can be printed (cf. Fig. 10.4). In addition, a function integration can be included, for instance in terms of electronic functionalities such as conductor tracks (cf. Fig. 10.5) or sensors that can be directly printed into three-dimensional components. In this way, digitization enables completely new possibilities for designing and manufacturing products.

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10.4 Mesoscopic lightweight construction using additively manufactured six-sided honeycombs

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Lightweight construction plays an important role in the aerospace and automotive industries in order to reduce the energy demand during operation or to raise the performance of the overall system. Beyond this, principles of lightweight construction are utilized in all sectors of industry to achieve ecological and economic use of raw materials. Nevertheless, ideal lightweight construction designs can often not be implemented because the corresponding manufacturing technologies for materialization are not available. Additive manufacturing techniques such as laser beam melting (LBM) can provide assistance here. The process operation can permit the manufacturing of geometrically complex components in small batches, highly efficiently.

Fraunhofer IGCV is working on optimizing lattice and honeycomb structures for sandwich components. In sandwich components, a lightweight core is supplied with solid, rigid covering layers producing a material compound that demonstrates significantly better mechanical properties than the sum of the individual layers. Honeycomb structures are thus particularly well suited for use as core material for high-strength lightweight constructions since the hexagonal geometry allows maximum compression loads to be absorbed with minimal core weight. Using conventional methods to manufacture honeycomb structures, however, produces significant limitations with respect to fully exploiting the potential of lightweight construction. This is due, on the one hand, to the fact that conventional, e.g. forming, manufacturing techniques produce regular material filling degrees that do not allow for load optimization of the structure. Conventionally manufactured honeycomb structures, for example, thus offer almost no possibility for placing more material at points of high load and reducing the material thickness of the honeycomb walls at points of low load. In addition to this, conventional techniques offer limited suitability for adapting the honeycomb structures to freeform surfaces. By using additive manufacturing on the other hand, honeycomb structures can be adapted to complex geometries (cf. Fig. 10.6).

To achieve this, Fraunhofer IGCV developed a software tool for the CAD program Siemens NX, which aligns the honeycomb with a given freeform surface and dimensions the honeycomb's individual segments in keeping with the load. In addition, inserts can be provided to introduce threads into the sandwich composite, for

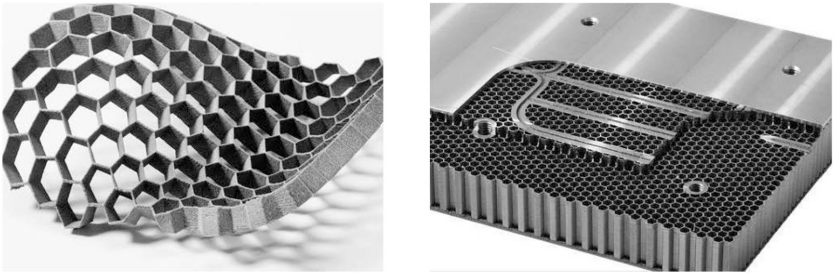

Fig. 10.6 Honeycomb structure adapted to a freeform surface, and honeycomb with load application elements (Fraunhofer IGCV)

example (cf. Fig. 10.6). By using powder bed-based additive manufacturing processes, the honeycomb structures produced in this way were able to be generated in both plastic as well as metal. Further potential for reducing weight and increasing rigidity lies in the combination of additively manufactured honeycomb structures with a covering layer of carbon fiber-reinforced plastic.

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10.5 Using biomimetic structures for esthetic consumer goods

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Together with our project partners Industrial Design, Folkwang University Essen, Fraunhofer UMSICHT, Sintermask GmbH, rapid.product manufacturing GmbH and Authentics GmbH, a numeric tool for design, analysis and optimization was developed at Fraunhofer IWM.[2] The tool fills specified external shapes with a cellular structure based on trabecular cells, similar to cancellous bone. For additive manufacturing to be cost-effective, it is important to be able to assess the mechanical properties of products without having to produce additional exemplars for mechan-

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[2] Bionic Manufacturing, DLR, part of the BMBF's Biona program (BMBF-FKZ 01RB0906)

Fig. 10.7 *Cellular Loop*, a mechanically developed and manufactured designer cantilever chair. Photo by Natalie Richter (Folkwang University of the Arts)

ical testing. Due to the regularity of the cellular structure, this approach facilitates the advance calculation of mechanical properties such as load-bearing capacity and rigidity. Experimental data from just a few representative samples is the only input parameter needed to characterize the material and the process for finite element models. Any additive manufacturing technique and material can be used here.

In order to optimize the component's mechanical properties, the trabecular cell's microstructure can be adapted to a given load. This is done by locally anisotropically increasing the diameter of the trabecular rods. In this way, the load-bearing capacity of the component can be significantly raised, with minimum material use and production time.

The tool presented can be used on a large number of components and allows mechanical properties to be calculated and improved. Due to its visual properties, the biomimetic cellular structure also leads to esthetically pleasing products, as shown by the product described in what follows.

As a demonstrator, a bionic cantilever chair was developed by the group around Anke Bernotat at the Folkwang University of the Arts. The loads produced by an individual sitting on it were calculated at Fraunhofer IWM. Next, the microstructure was adapted to this load. The shape was divided into producible segments and the chair was then manufactured in selective-laser-sintering by our partners at rpm-factories. The chair provided the expected load-bearing capacity and also corresponds to the highest esthetic standards.

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10.6 High-performance tools for sheet metal hot forming using laser beam melting

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Manufacturing complex sheet metal parts from high-strength steel places large demands on cold forming. High pressing forces and the relatively high springback represent huge challenges. Very rigid tools made of expensive material are required that are nevertheless subject to increased wear. An alternative to cold forming is sheet metal hot forming or press hardening. Here, the sheet metal blank is heated above the austenitizing temperature (above 950 °C) and rapidly cooled to below 200 ºC during forming, creating a martensitic structure.

The structure of a hot forming tool is more complex than that of a conventional one. The reason for this is the necessary integration of cooling channels into punch and die. The channels, generally produced by deep drilling, are limited in their minimally representable diameters, which has a direct impact on the contour dis-

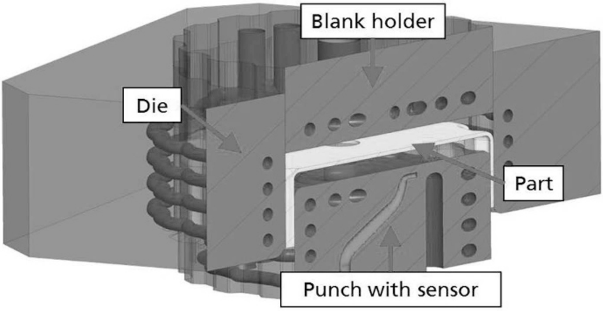

Fig. 10.8 3D CAD model of a press hardening tool with conformal cooling channels (Fraunhofer IWU)

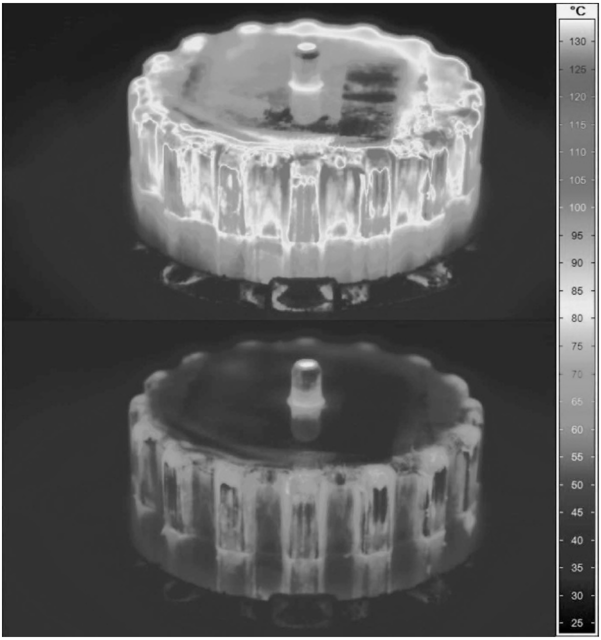

Fig. 10.9 Thermographic image of a tool punch (Fraunhofer IWU)

tance achievable. For this reason, targeted tempering of individual regions conformal to the contour of the tool is only achievable with great effort and significant limitations for hot forming tools. This often causes insufficient target temperature achievement and too little heat dissipation in the tool's critical regions.

As part of the additively manufactured HiperFormTool[3] project, research has been carried out into how sheet metal hot forming can be made more efficient by means of additively manufactured active tool components. To achieve this, the thermal behavior of the tools and of the forming process was precisely analyzed via simulation and various cooling channel geometries compared. Based on the results of the simulation and by using the geometric freedom of additive laser beam melting, an innovative and contour-close cooling system was developed. The primary goal of the research studies was to significantly shorten the cycle time. In addition, a concept for sensor integration during the additive manufacturing process was developed and implemented.

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[3] HiperFormTool, high-performance sheet metal hot forming tools using laser beam melting, ERA-NET joint project, MANUNET HiperFormTool (BMBF-FKZ 02PN2000)

The innovative cooling system allowed a significant reduction of holding time in press hardening of 70%, from 10 s to 3s, with hot-formed components of identical precision and hardness. In total, more than 1,500 components were formed and 3 hours of manufacturing time saved in the process. The function of the firmly bonded integrated thermosensors could be proven through the precisely documented temperature progress during the laser beam melting process itself, the heat treatment, and the actual forming tests.

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10.7 Additive manufacturing of ceramic components

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In contrast to the additive manufacturing of polymer or metal components, in ceramic component manufacture the typical heat treatment processes such as debinding and sintering follow the actual additive manufacturing process (shaping). Here, the organic additives are first removed from the additively manufactured green body

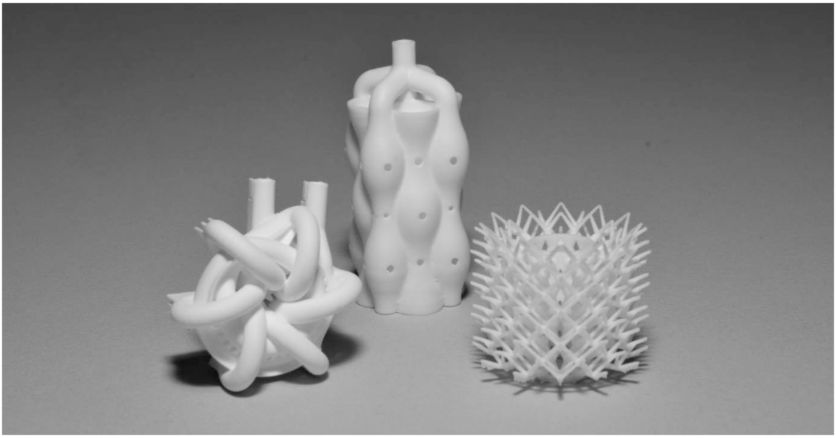

Fig. 10.10 Additively manufactured aluminum oxide components for applications as heat exchangers or mixers for two fluids (Fraunhofer IKTS)

before the ceramic particles are sintered, which generally involves a significant reduction in volume, at temperatures above 1000 ºC. It is only during the sintering phase that the component gains its final properties.

For manufacturing ceramic components additively, different processes are used that can generally be divided into powder bed- and suspension-based or indirect processes (areal application of the material and selective solidification) and direct processes (selective application of the material).

With suspension-based processes, the base materials are in the form of suspensions, pastes, inks, or semi-finished products such as thermoplastic feedstocks, green sheets, or filaments. Compared with powder bed-based processes, higher green densities are achieved with suspension-based additive manufacturing processes, which then lead to a dense microstructure in the sintered part and decreased surface roughness. New, complex ceramic structures illustrate the potential of additive manufacturing for ceramic (cf. Fig. 10.10).

One current focus is on the development of processes for manufacturing multi-material compounds (e.g. ceramic/metal) and components with a gradient of properties (e.g. porous/dense). The direct processes in particular offer huge potential here due to the selective application of different materials. In this way, in future it will be possible to manufacture components with highly complex inner and outer geometries that will also combine the properties of various materials (e.g. electrically conductive/non-conductive, magnetic/non-magnetic).

Materials, equipment, process, and component development issues are being worked on together with national and international partners in several BMBF pro-

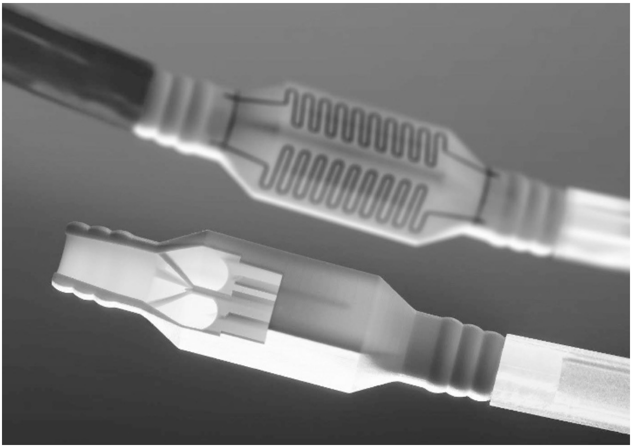

Fig. 10.11 Ceramic heating element structure, additively manufactured and functionalized using aerosol printing (Fraunhofer IKTS)

jects (AGENT-3D: IMProve + MultiBeAM + FunGeoS; AddiZwerk) and within the EU project cerAMfacturing. An additional area of focus is the development of hybrid processes, where additive and conventional manufacturing techniques are combined. Using this technique, it is possible to further customize components that are mass produced, or to further functionalize additively manufactured components (cf. Fig. 10.11). Alongside the development and adaptation of the process, the constant broadening of the useable material portfolio is obviously also an indispensable development task.

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10.8 Printable biomaterials

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Printing biological and biofunctional materials – also known as bioprinting – is a relatively new and promising option for giving surfaces a function or manufacturing entire 3D objects (cf. Fig. 10.12). Current research and development studies that Fraunhofer IGB is involved in provide fuel to the vision of one day using customized biological implants.

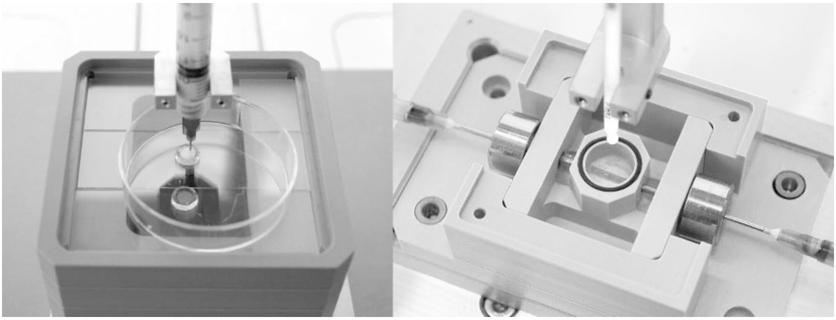

Fig. 10.12 Bioinks made of modified biomolecules are designed for digital generation of biological tissue replacements. The modified biomolecules at Fraunhofer IGB can be formulated to form low or high viscous fluids and composed to host different cell types. Left: viscous ink for bone cells, right: soft ink for sensitive fat cells.

Various printing techniques such as inkjet or dispensing processes require different rheological material properties. At the same time, the so-called bio-inks must be stabilized after printing so that the desired biological functions are available.

Biopolymers are optimized by nature and fulfill complex tasks: as matrices of tissue they harbor living cells for example; they store water and water-soluble substances and release them on demand; and they are involved in the transmission of biological signals. These extensive functions cannot simply be reproduced via chemical synthesis, but it is possible to chemically modify suitable biomolecules and thus make them usable for digital printing processes.

Fraunhofer IGB uses biopolymers from the extracellular matrix of natural tissues such as gelatin as a derived product from collagen, heparin, hyaluronic acid, and chondroitin sulfate, and provides them with additional functions. By "masking" specific functional groups, for example, intermolecular interactions can be reduced and the viscosity and gelatinization behavior of the biopolymer solutions thus influenced. In addition, reactive groups can be adapted in order to fix biomolecules onto surfaces and produce hydrogels of variable strength and swelling capacity, see Fig. 10.13. [2][3][4][5] Finally, by means of the formulation – that is, the mixing and addition of signal substances or biofunctional particles – printable biomaterials with tailored properties are produced. [6][7]

With chemically modified biopolymers as a basis, Fraunhofer IGB develops printable biomolecule solutions, bio-based release systems, and cell-specific matrices for tissue regeneration. [8][9][10]

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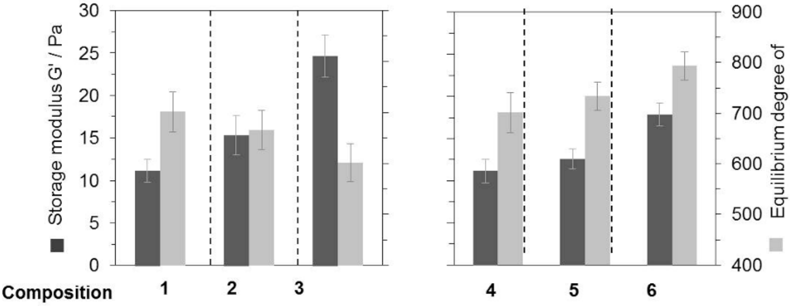

Fig. 10.13 Via the formulation of differently modified biomolecules, hydrogels with the same biopolymer concentration and composition can be produced with different combinations of properties (Fraunhofer IGB).

10.9 Development and construction of a highly productive manufacturing facility for additive manufacturing of large-scale components made of arbitrary plastics

Dr. Uwe Klaeger
Fraunhofer Institute for Factory Operation and Automation IFF

In many sectors, manufacturing large components is associated with high production costs. In order to be able to produce these kinds of elements economically, high build-up rates (production speeds) and simultaneously low material costs are required.

One promising approach to solving this problem is the development of a new, inexpensive plant concept, which is being pursued within the High Performance 3D joint project[4] by six industrial companies and three research institutes.

The technology combines additive manufacturing techniques with modern industrial robotics, thus facilitating the economical manufacture of individual components of arbitrary sizes and weights.

The fundamental idea behind this process is based on the combination of a special granulate extruder with a flexible buckling arm robot. The highly productive plant uses three extruders that can be utilized to apply different materials layer-by-layer. The materials palette includes both hard/soft combinations and different colors as well as materials filled with glass or carbon fibers. The extruder unit was designed for a maximum component build-up rate of 2 kg/h for standardized granulates, typical plastic materials such as ABS, PMMA, PP, PC, PC/ABS, and PLA. To guarantee a continual flow of material, a modified needle nozzle was fitted to prevent uncontrolled filament formation during the construction process. By constantly measuring the online temperature in the installation room, stable viscosity behavior of the plastics is achieved.

Component construction takes place on a heated work platform mounted to the robot. In order to produce a three-dimensional part without anisotropy, the construction platform moves on six axes so that the material application point is always perpendicular to the extruder nozzle. A second robot places additional elements into the component (including metallic ones), thus facilitating the automatic integration of additional functional elements. The prototype plant is initially designed for com-

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[4] HP3D: Concept development and construction of a highly productive manufacturing plant for additive manufacturing of large-scale components made of arbitrary plastics-High Performance 3D (BMBF-FKZ 02P14A027)

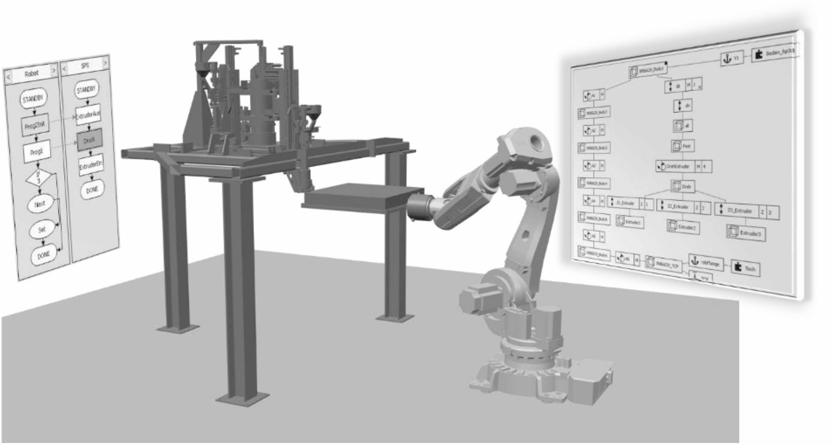

Fig. 10.14 Additive manufacturing of large components using universal industrial robotics and simulation tools to assist development (Fraunhofer IFF)

ponent volumes of 1000 x 1000 x 1000 mm³ and maximum component weights of 25 kg.

A key element of the overall technological concept is the simulation of complex production processes associated with development. To do this, the VINCENT universal simulation tool developed by Fraunhofer IFF is used (cf. Fig. 10.14). The results of the simulation are directly incorporated into the constructive development of the manufacturing plant. The program facilitates process visualization and reachability testing of all paths for the layer-by-layer component construction as well as a collision detection in the workspace. In this way, a geometric and functional test of the plant is possible even before commencing the manufacture of its components so that a significant reduction in the plant development and commissioning time is achieved.

The new 3D printing process combining extruders and robots opens up new possibilities in the production of large, complex, plastic parts. Since expensive molds or tools are not required, component production is subject to hardly any spatial limitations. With the significantly shorter process chain, large components will in future be able to be produced economically and flexibly, leading to a variety of new or improved products in a large range of market segments.

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10.10 Integration of sensory-diagnostic and actuator therapeutic functions in implants

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Both diagnostic as well as therapeutic functions are expected from theranostic implants. In engineering terms, then, implants should have sensory and actuator components integrated into them. The advantage of this kind of strategic approach is that treatment-relevant information can be gathered where it arises so that biological treatment effects can be achieved locally precisely there. This strategy was implemented in the Fraunhofer Theranostic Implants lighthouse project in terms of a form-fit, force-fit bonded embedding of actuators and sensors into a compact additively manufactured hip implant. By means of this complete integration in the implant, the measurement of forces or stresses can thus take place directly in the region where they occur within the implant.

For therapeutic functions, the corresponding actuator module, hermetically encapsulated in the interior of the implant, can ensure a partial or total excitation of the implant close to the desired surface area for biomechanical, electrical, or chemical

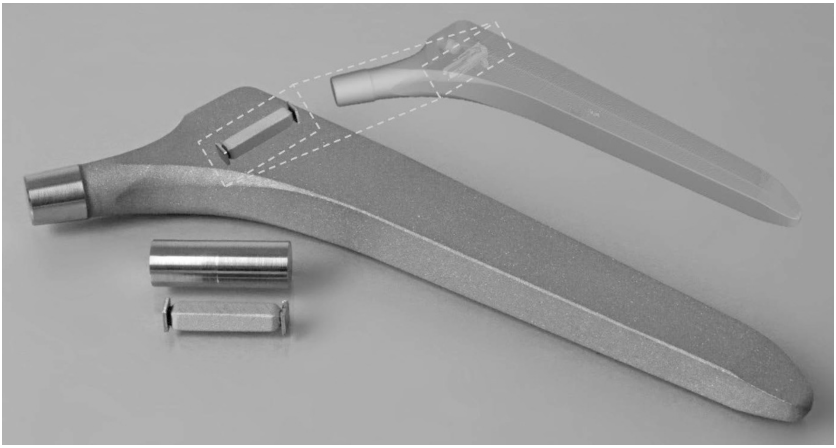

Fig. 10.15 Hip stem implant with integrated sensor-actuator unit; top right: CT image (Fraunhofer IWU)

excitation of the interface between the implant and the tissue. As a result of this project, it was possible to integrate thermally sensitive functional components into a titanium hip stem implant produced additively via laser beam melting. To do this, both the sensor/actuator and inductor for the wireless energy and data transmission were incorporated into an additively manufactured carrier structure that is welded with the main body of the implant later in the process. Therefor, the inherent properties of the additive manufacturing process are used to apply thermal energy into the material in a spatially and temporally highly limited and highly controlled manner using the laser beam. Combined with a suitable laser beam process control and a specially developed additively manufactured ceramic-metal multilayer protective coating system (ceramic metallic covering – CMC) for the sensors/actuators, it was possible to ensure that the functionality of the sensors/actuators was retained in spite of the high melting temperatures of the TiAl6V4 titanium alloy of almost 1700 °C. The process chain developed for the form-fit, force-fit, firmly bonded integration of the sensors/actuators can be transferred to additional applications and used for component-integrated condition monitoring or actuator functionalization for example.

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10.11 Generating three-dimensional multi-material parts

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Fraunhofer IGCV’s Additive Manufacturing group is currently working primarily on powder bed-based techniques for producing high-performance metal components such as laser beam melting (LBM). Here, a laser beam is used to selectively melt and solidify thin layers of metal powder. At present, the process can be used to produce components made of a single material. Multi-material components are characterized by at least two different materials that are firmly joined to one another. The manufacture of 2D multi-material components, which feature a change of material between subsequent layers, is already possible by means of time-consuming manual changes of material. At present, this is typically not possible for a 3D multi-material component since both materials must be present within a single

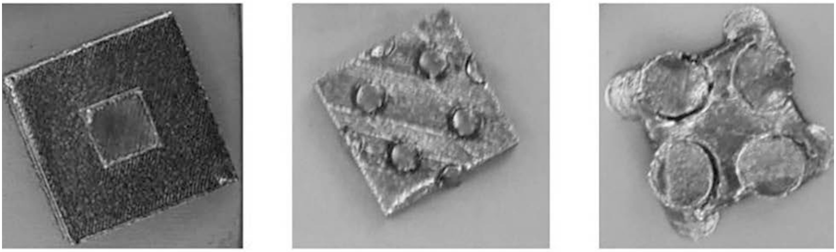

Fig.10.16 Multi-material structures with 1.2709 tool steel and copper alloy CuCr1Zr (Fraunhofer IGCV)

layer here. To manufacture these parts, it is necessary to adapt the powder application mechanism in order to facilitate the deposition of a second material in the powder layer. For this reason, at Fraunhofer IGCV, a new application mechanism was integrated into an LBM plant via software and hardware so that the construction of 3D multi-material components is now possible in a laser beam melting system.

An initial application of the modified laser beam melting system focused on the production of structures made of 1.2709 tool steel and a copper alloy (cf. Fig. 10.16) within the project ForNextGen supported by the Bavarian Research Foundation. The project consortium consisting of six academic partners and 26 industrial companies has the goal of laying manufacturing science foundations for the use of additive manufacturing processes in mold and tool making, and is being supported by the Bavarian Research Foundation. The classifying and subsequent introduction of these processes is intended to lead to significant improvements in the complexity of shapes, strength, and production time and cost of tools in primary shaping and forming. The multi-material processing researched by Fraunhofer IGCV thus offers great potential for tool shapes and uses. Using the example of a sprue bushing for a die casting mould, a base body of 1.2709 tool steel is constructed and equipped with CuCr1Zr (copper alloy) in two different component regions for improved heat dissipation. By means of these internal cooling structures made of highly thermally-conductive material, the heat balance can be improved and the cycle time thus reduced.

Beyond the work carried out as a part of the ForNextGen project, Fraunhofer IGCV could already show that the current laser beam melting system can even be used to produce multi-material components of metal alloy and a technical ceramic (AlSi12 and Al_2O_3).

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