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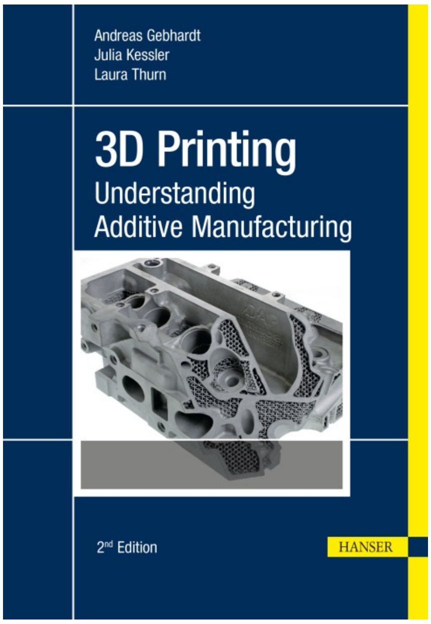


# Sample Pages

# 3D Printing

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# Preface

Additive manufacturing (AM), 3D printing, desktop manufacturing, and some others are identical terms for the technology of layer-based manufacturing and its application.

The different terms describe these new manufacturing processes, from which the establishment of another industrial revolution is expected. They are suitable for acceleration of product development by production of complex prototypes quickly and with improved quality. But they also allow production of final parts, independent from the size of the lot.

Thus, they indeed mark a revolution in manufacturing techniques: the change from a production technology for the manufacture of large series of identical parts to a mixed series production of different parts, even down to one-of-a-kind parts.

3D printing is applicable in all branches of industry. Anybody engaged in engineering design and production, but also in strategic product planning, should know at least the basics of AM in order to perform a qualified evaluation and selection of the best applicable technology.

This book, *3D Printing*, is a new edition of *Understanding Additive Manufacturing*, which was originally published in 2011. It has been extensively updated and expanded to reflect the major new developments in the field that have taken place since then.

Suitable for the practitioner, this book imparts a basic knowledge of the processes and thoroughly demonstrates exemplary applications. Almost all currently available machines are presented in a systematic way that also allows the classification and evaluation of future systems. The large and fast-growing variety of different machines for additive manufacturing processes is also classified.

Besides processes, also discussed are new working strategies that result from the digital, mixed production, allowing a decentralized manufacture that could thoroughly change the organization of today's production.

A glossary is provided to clarify common terms and abbreviations used in 3D printing, and so to assist a quick approach into AM.

Aachen, November 2018 *Andreas Gebhardt, Julia Kessler, and Laura Thurn*

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**Figure 2.10** Micro stereolithography, parts and MEMS (microelectromechanical systems) (Source: microTEC)

### 2.1.2 Sintering and Melting

Selective melting of plastic and metal powders that show thermoplastic behavior and re-solidification after cooling is called *laser sintering*. Depending on the manufacturer it also is named *selective laser sintering*, *laser cusing*, or in case of metal *laser melting*. Processes, using an electron beam instead of a laser are called *electron beam melting* (EBM). If the energy is supplied by means of a heat radiator (infrared) and contoured by a mask, the process is called *selective mask sintering*.

#### 2.1.2.1 Laser Sintering/Selective Laser Sintering (LS/SLS)

The terms *laser sintering* and *selective laser sintering* are primarily used for machines that process plastics. Manufacturers include 3D Systems, Rock Hill, SC, USA; EOS GmbH, Munich, Germany; and Prodways, Les Mureaux, France and Plymouth, MN.

The machines of all manufacturers processing metals are very similar. They consist of a build space, filled with powder of a grain size of approximately 20–50 µm, and a laser scanner on top that generates the x-y-contour. The bottom of the build space is designed as a movable piston, which can be adjusted to any z-elevation (Figure 2.11)[1]. The surface of the powder bed forms the build area, where the current layer is generated. The complete build space is heated, to minimize the laser power and to reduce deformations. To avoid oxidation, the build space is flooded with shielding gas.

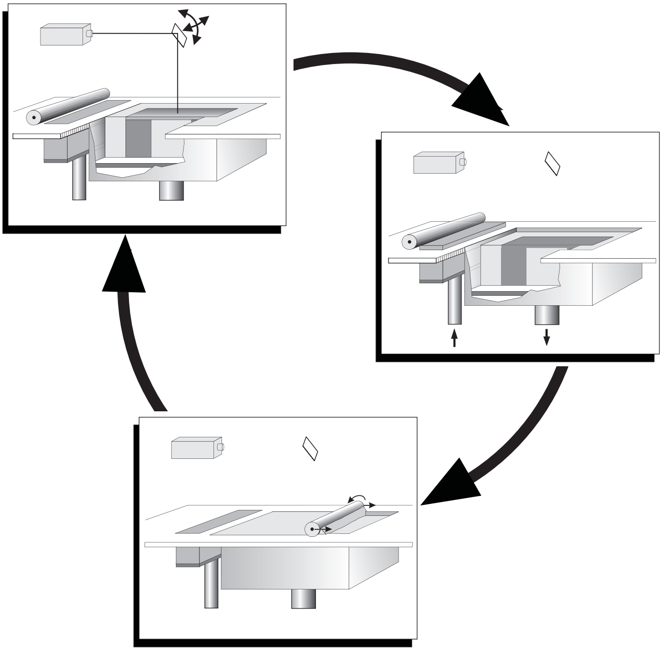

**Figure 2.11** Laser sintering and laser melting, schematic procedure; melting and solidifying of a single layer; lowering of the build platform; recoating (clockwise, starting from top left)

Each layer is outlined by the laser beam. The contour data is generated from the slice data of each layer according to the 3D CAD model and managed by the scanner. Where the laser beam hits the powder surface, the particles are locally melted. The process depends on the diameter of the laser beam and on the scan speed. While the beam continues to move the molten material solidifies due to the heat transfer by thermal conductivity into the surrounding powder. Thus, a solid layer is generated.

After the solidification of a layer the piston at the bottom of the build space is lowered by the amount of one layer thickness, which also means that the complete powder bed and the growing part is lowered. The free space above the powder bed is refilled with fresh powder, which is taken from the adjacent powder reservoir by means of a roller.

[1] A 3D animation can be found under: www.rtejournal.de/filme/SLS-RTe.wmv/view

To achieve an even distribution of fresh powder, the roller rotates opposite to the direction of the linear movement of the coating device. This procedure is called *recoating*.

After the recoating the build process starts again, generating the next layer. The complete process is continued layer by layer until the part is finalized. Usually the top layer is manufactured by using a different scan strategy to increase the strength.

After the manufacture is completed and the top layer has been generated, the complete part inclusive the surrounding powder is covered with some additional powder layers. This so-called powder cake has to be cooled down before the part can be taken out of the surrounding powder and be removed. The cooling procedure can be carried out inside of the machine; however, cooling down in a separate chamber allows the immediate start of a new build process.

Sintering allows the processing of all kinds of materials like plastics, metals, and ceramics. Basically, the machines are very similar in design. The machines are either adapted to the different materials by software modifications (and possibly by minor hardware modifications) or special versions of a basic machine type are optimized to process a distinctive kind of material.

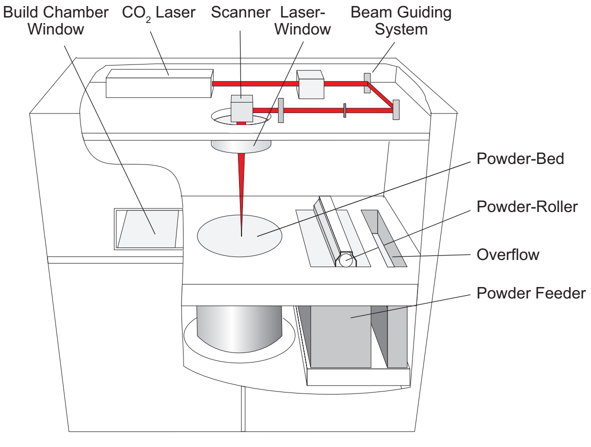


**Figure 2.12** Basic design of a sintering machine from 3D Systems (left), laser sintering machine EOSINT P 800 (right)
(Source: 3D Systems/EOS GmbH).

In this context the recoating systems are specially adapted to handle the materials, chosen for the application, for example roller systems for plastic powders as well as hopper systems or filling shoes for plastic coated foundry sand. For metal processing systems, also wiper-type devices are applied.

While standard plastic materials are polyamides of type PA 11 or PA 12, today high-performance materials emulate the properties of PC, ABS, and PA (6.6) plastics, and generate design elements like film hinges and snap-fits. The high-temperature system EOS/P 396 (2017) is the only available system on the market that also processes high-performance plastics (in this case PEEK) and is a trend setter.

For *laser sintering*, unfilled materials and materials filled with spherical or egg-shaped glass, aluminum, or carbon particles, which increase their strength and temperature resistance, are on the market. Flame-resistant materials are also available.

The removal of the part from the powder (the so-called *break out*) is done manually by using vacuum cleaners, brushing, or shot blasting on low pressure.

Semi-automatic break-out stations make work easier and mark the trend to automated cleaning. Metal parts have to be cut manually from the build platform and the supports, which is time-consuming and requires manual skills.

Plastic parts often are porous and need to be infiltrated. If required, surface treatment can be applied, or they can be varnished. Typically, metal parts are dense. Depending on the type of material, they can be processed conventionally, e.g. by cutting or welding.

Sintered plastic parts have properties that are close to those of plastics injection molded parts. They are manufactured either as prototypes (Figure 2.13, left) or as (directly manufactured) parts (also called target parts or series parts) (Figure 2.13, right).

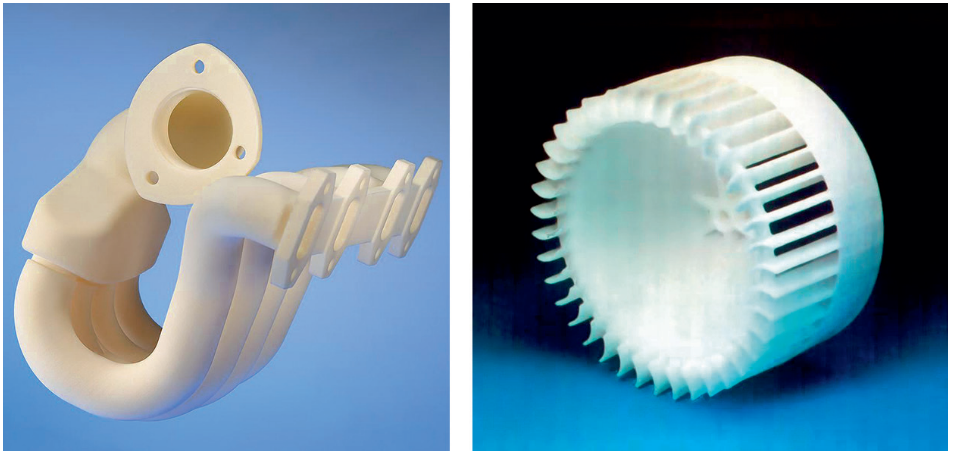

**Figure 2.13** Selective laser sintering, SLS (3D Systems): engine exhaust manifold; prototype, polyamide (left); fan rotor, final part (right)
(Source: CP-GmbH)

### 2.1.2.2 Powderbed Fusion (PBF), Selective Laser Melting (SLM)

Basically, *laser melting* is very similar to the above-described laser sintering process. It was specially developed for manufacturing of very dense (> 99%) metal parts. The material is totally melted by the laser. Therefore, it generates a local (selective) melt pool, which results in a completely dense part after solidification. Generally, the process is named *selective laser melting* (SLM).

Some proprietary terms exist, such as *cusing*, a combination of the words *cladding* and *fusing*.

Most of these machines have their origin in Germany:

- EOS GmbH, Munich
- Realizer GmbH, Borchen
- Concept Laser GmbH, Lichtenfels
- SLM Solutions, Lübeck
- Some of these companies have been acquired by US-American companies like GE (General Electric)

  Moreover, 3D Systems, Rock Hill, SC, USA offers the ProX series, re-branded systems based on the PHENIX process, which is called direct *metal sintering (DMS)*.

  Renishaw developed and offers the machines AM 125 to AM 500, which were taken over from MTT, Great Britain, under their own name.

  For all metal processing machines, a wide variety of metals, including carbon steel, stainless steel, CoCr-alloys, titanium, aluminum, gold, and proprietary alloys is available. Typically, metal parts are final parts and are used as (direct manufactured) products or elements of such products. Characteristic examples are the internally cooled *cooling pin inserts* from tool steel shown in Figure 2.14 (left), which are used for local cooling of injection molds, and the micro-cooler made from AlSi10Mg in Figure 2.14 (right).

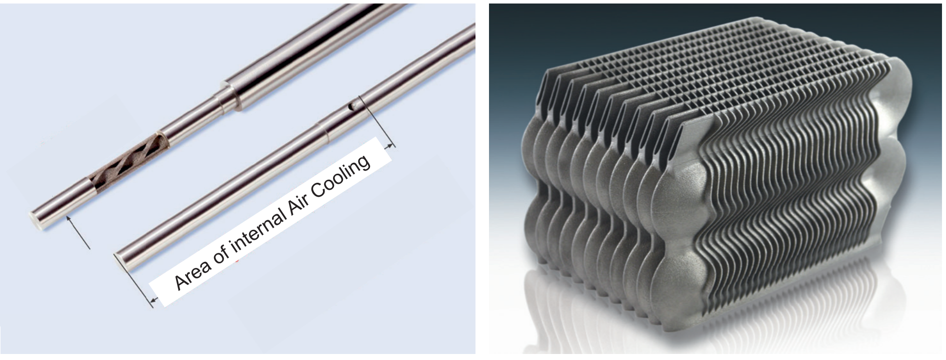


**Figure 2.14** Selective laser melting, SLM: internally cooled pin for application in injection molds (left); micro-cooler, made from AlSi10Mg (right)
(Sources: Concept Laser GmbH (left); EOS GmbH (right))

## 3.2 Machines for Additive Manufacturing

As already mentioned in Section 1.3 "Classification of Machines for Additive Manufacturing", the large and fast-growing variety of different printers (machines) can be split into four classes. The four classes or categories of AM machines are *personal printers*, *professional printers*, *production printers*, and *industrial printers* (see Figure 3.6).

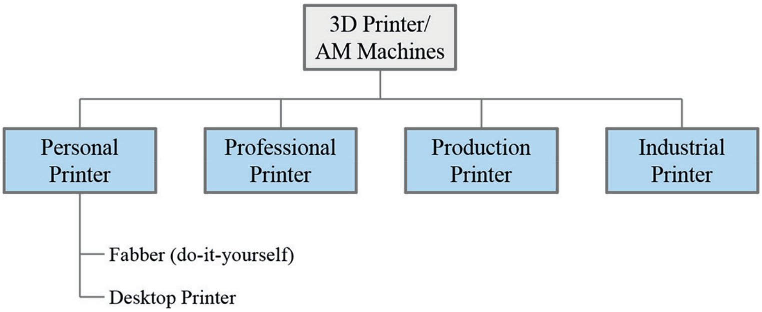


**Figure 3.6** Classification of 3D printers/AM machines

In Table 3.1 the four classes of AM machines are assigned to the application levels and classes as well as to the predominantly applied build material.

Apart from the classification of AM machines according to their application levels and fields, they differ explicitly in relation to the used materials, the accuracy (resolution), and the maximal load of the parts, but also with regard to the complexity of the parts.

**Table 3.1** Classification of Machines for Additive Manufacturing

| | **Machine Class** | | | |
|---|---|---|---|---|
| Designation | Personal printer | Professional printer | Production printer | Industrial printer |
| Application | Private/semi-professional | Professional | Professional/ (industrial) | Professional/ industrial |
| Build material | Plastics | Plastics, metal | Plastics, metal, ceramic | Plastics, metal |
| **Application Level (see Figure 1.1)** | | | | |
| Prototypes | X | | | |
| Concept models | X | | | |
| Functional parts | | X | | |
| Final products | | | X | X |

The company SinterIt from Kraków, Poland was the first to develop a powder printer in desktop size with the aim to spread laser sintering to the wider public. The machine *LISA* was presented for the first time on the Hannover Fair 2016 and can be ordered internationally online.

LISA (Figure 3.12) works according to the laser sintering process and processes PA 12, with layer thicknesses up to 0.06 mm.

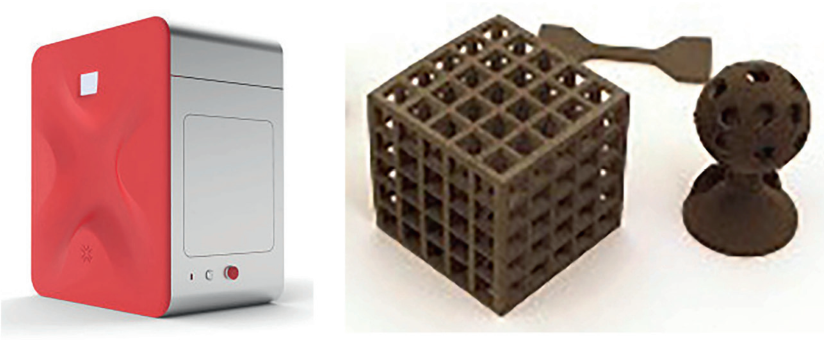

**Figure 3.12** Individualized manufacturing of final parts: desktop printer LISA (left); "low-cost sintering" parts, made from PA 12 (right)
(Source: SinterIt)

### 3.2.2 Professional Printers

Professional 3D printers show the typical characteristics of AM processing centers. This requires an organized workshop. Programming is independent of the build process and increases the overall flexibility. Some manually executed program steps are already integrated and are processed (partly) with automation; this, for example, is the case for closed material cycles. The sequence of the program is completely automated. There are the rudiments of process monitoring. The operator gets feedback from the system.

Professional printers are stand-alone machines for the fabrication of functional parts (see Table 3.5). The main application of professional printers is the commercial use in the office or workshop. For most of the printers no special infrastructure is required, only a plug point and a table. A separate office room makes handling of material and parts easier and reduces the noise emission, which generally is not significant.

Table 3.6 provides an overview regarding professional printers with respect to machine prices and materials, and marks advantages and disadvantages of the machines.

**Table 3.5** AM Machines: Category Professional Printers (Office Machines)

|  |  |  |  |
|---|---|---|---|
| **Agilista-3200W**<br>Keyence | **Dimension Elite**<br>Stratasys | **Objet 30 prime**<br>Stratasys | **ZPrinter 450**<br>3D Systems |
| Plastics<br>*Polymer printing* | Plastics<br>*Extrusion* | Plastics<br>*PolyJet* | Gypsum plaster<br>*3D printing* |

**Table 3.6** Professional Printers: Overview (Characteristics)

| **Professional Printers** | |
|---|---|
| Prices of machines | From approx. €20,000 up to approx. €70,000 |
| Software | Manufacturer-specific, plug & play |
| Build Materials<br>(depending on process/machine) | Plastics, ceramics, metals, gypsum-starch powder |
| Advantages<br>(depending on process/machine) | ▪ Preset parameter sets<br>▪ Minimal/no infrastructure required<br>▪ Short training<br>▪ Office infrastructure |
| Disadvantages<br>(depending on process/machine) | ▪ Partly high material costs<br>▪ In part, the user depends on the manufacturer of the machine (software/material) |

### 3.2.3 Production Printers

Production 3D printers (see Table 3.7 and Table 3.8) show the characteristics of flexible additive manufacturing units. They may come as stand-alone machines but increasingly they are designed as AM processing centers, which are equipped even with integrated automated peripheral devices, like de-powdering stations. Characteristics are additional features that enable a detailed operational planning like nesting on the job, precise build-time estimators, or even simulators of the manufacturing process. The common target of production printers is an operation with a minimum of manual process steps, a mixed operation regarding the parts, continuous manufacturing, and production change free of preparation, etc. All these are characteristics that are regarded as advancements on conventional subtractive manufacturing, and can be considered as system-inherent with regard to AM. Current examples are the production printers of SLM Solutions (see Figure 3.13) and EOS (see Figure 3.14).

**Table 3.7** AM Machines: Category Production Printers

|  |  |  |  |
|---|---|---|---|
| **ProX® 950**<br>3D Systems | **VX2000**<br>Voxeljet | **M3 Linear**<br>Concept Laser | **P800**<br>EOS GmbH |
| Plastics<br>*Stereolithography* | Plastics<br>*3D printing* | Metal<br>*Laser cusing/Laser melting* | Plastics<br>*Laser sintering* |


**Figure 3.13** SLM® 500 HL: Laser melting units including unpacking unit PRS (to the left) and powder screening station (middle)
(Source: SLM Solutions)

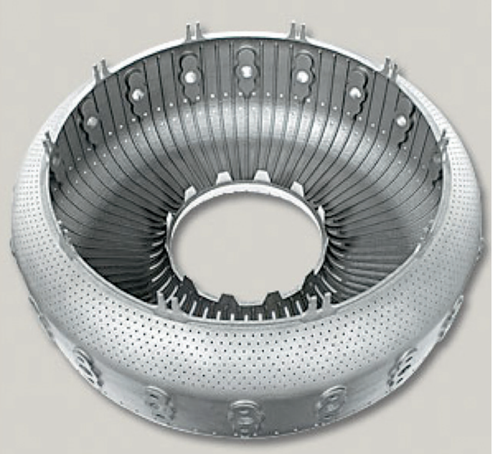

**Figure 4.8** Combustion chamber element: selective laser melting (SLM) (Source: Concept Laser/GE)

Directly printed parts made from metal are successful from technological and economic perspectives if they are optimized with regards to geometry and function. AM offers the opportunity to apply a bionic design strategy, thus raising the potential for lightweight design (see Figure 4.9).

**Figure 4.9** 3D printed lightweight bracket, for the A350 XWB; SLM, titanium (Source: Airbus)

It can be seen immediately that the parts look different from traditionally designed ones. Thus, they show that for a fast and effective execution of AM an AM-suitable design is mandatory; see Section 6.2 “Construction – Engineering Design”.

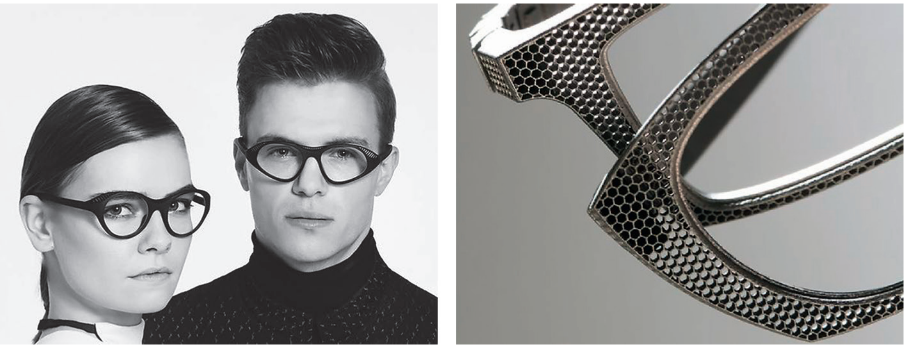

**Figure 4.14** Customized frames for glasses: laser sintering, titanium (Source: Hoet)

For example, the Hoya company presented at Opti 2017 – the international trade show for optics and design in Munich – an extensive program of customized spectacles frames. The system "Yuniku" also includes a scanner that records faces, facilitating the choice of suitable glasses and preparing the additive manufacture of the individual frame. The program was developed in cooperation with designers as Hoet (Brugge, Belgium) and Aoyama (Villeneuve d'Ascq, France) with technical support by Materialise. This approach was further developed into an internet-based tool, accessible to customers, which integrates the individual data into the 3D-printable frame design.

The extravagant sandals in Figure 4.15 can be considered as archetypes of individually designed, trendy shoes, which moreover can be manufactured in any size and height – as desired. As these objects can be used directly, they can be considered as products and thus the manufacturing process belongs to *rapid manufacturing*. Although the sample sandals were made by means of laser sintering from polyamide, extrusion and polymerization processes can also be applied with the correspondingly appropriate materials, including soft types like TPU and TPE.


**Figure 4.15** "Paris Sandals", high heels: laser sintering, polyamide (Source: Freedomofcreation, FOC)

The application of additive processes for the production of musical instruments was already presented in 2012 by Professor Olaf Diegel at the Massey University in Auckland, New Zealand with an example of a laser-sintered electric guitar made from polyamide.

In May 2016 the first 3D printed guitar made from aluminum was presented. The complete body of the guitar was manufactured in one piece on the machine EOS M400 (Source: Xilloc; see Figure 4.16).

**Figure 4.16** 3D printed guitar made from aluminum, SLM (Source: Xilloc/Diegel)

Meanwhile different service bureaus offer customized 3D prints from individuals. Full-body scanners with up to 80 digital cameras arranged inside a tube at different angles instantly acquire a 3D photographic image and thus a 3D data set. The advantage of this kind of scanner is that the recorded person does not have to keep still. It can thus be used for children, animals, and moving individuals. The up to 80 photos taken are loaded into a software application and automatically assembled to form a solid body. However, an additional manual post-processing needs to be applied and requires extended know-how in the field of image processing. The data set usually is printed by means of 3D printing (powder-binder process); see also Section 2.1.4 “Powder-Binder Process” and Figure 4.17. The post-processing of the mostly fine, delicate structures is based on infiltration but, depending on the desired quality, is laborious and time consuming. Alternatively, polymer jetting can be applied.

**Figure 4.17** Body scanning and AM by means of 3D printing: powder binder process (Source: Nathalie Richards (left); Caters New Agency (right))

Furthermore, the creative work of artists can be successfully supported by additive manufacturing processes. Sculptors often use clay models to build up and manually improve their work stepwise before final casting. Alternatively, a handmade model can first be scanned and transformed into an AM part from polyamide (by sintering) or plaster (by 3D printing). This master model can be improved manually, to reflect the "handwriting" of the artist, and then be transferred via a wax model (obtained by RTV) into a series of unique specimens, cast from bronze.

## ■ 4.4 Toy Industry

Although toys are regarded as consumer goods, the toy industry usually is considered separately. The majority of this industry involves the series production of plastic parts for children's toys, but increasingly also individualized models, mainly of automobiles, aircraft, and railroads, are focusing on adult clients. These models require fine details and a sensitive scaling that considers small and large details differently. Depending on the scale, some AM processes are more suitable than others. Figure 4.18 shows a model of a toy steam engine in scale G (1:22.5) that, including its tender, is about four feet long. For the manufacture of this object the layer laminate process is a good option, because the material is inexpensive, and the details are not too small. For this kind of (showcase) model, physical properties, such as load-bearing capacity, and very fine details are less important than the overall appearance.

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