3-D Printing for Production

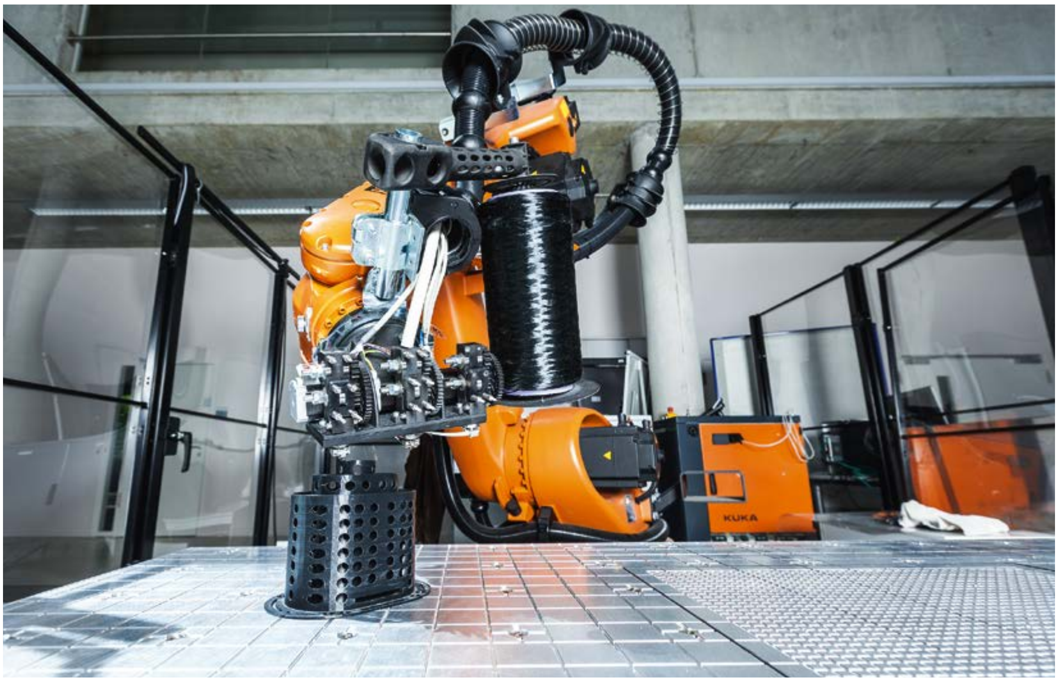
Additive Manufacturing with Thermoplastics

3-D printing is increasingly being touted as the ultimate solution for the production world of the future. It remains to be seen whether that is justified – at any rate the bandwidth of applications and technical developments continues to grow steadily. That applies particularly to the possibilities of additive manufacturing with thermoplastics – recently also with endless-fiber-reinforcement.

The term additive manufacturing (AM) covers all the manufacturing processes that generate parts by building them up in layers. In the media, these processes, known as 3-D printing, became familiar in a wide range of scenarios, ranging from printed handguns, such as the Liberator .380 from Cody Wilson through the car body of the Strati from Local Motors to parts for house building, printed with the "KamerMaker."

Several Established Processes

The common feature of these examples is that the parts mentioned were produced with the same process, namely thermoplastic-based additive extrusion, which was first patented in 1992 by the US-company Stratasys. Now, there are both round-cord and pellet-based systems. Round-cord or filament-based systems from Stratasys are still grouped under the term fused deposition molding (FDM) and mainly process acrylonitrile-butadiene-styrene (ABS). Such systems by other manufacturers are grouped under the term fused layer modeling (FLM). The many 3-D printers for the home market are for the most part filament FLM systems and through their massive boom have helped to increase the familiarity of additive manufacturing enormously.



The 3-D printing of a part with the "3D Fibre Printer" is based on FLM with feeding of endless fibers into the thermoplastic melt (figure: Agor)

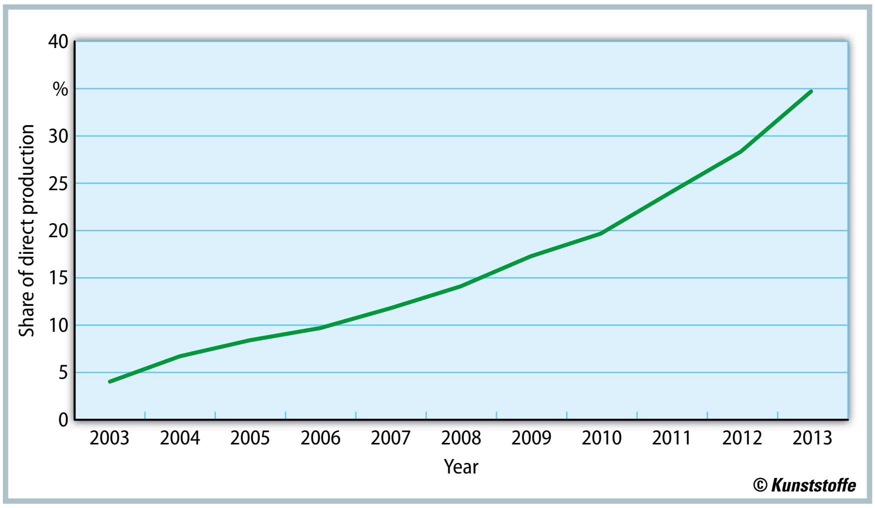


Fig. 1. Percentage share of direct production in the global AM part volume. Thanks to the higher quality, faster manufacturing rates, and wider choice of material, the additive production of parts and end products has increased its share compared to the manufacture of prototypes (source: Wohlers Report 2014)

Another group of processes that also processes thermoplastics as the material for the parts is sintering. Selective laser sintering (SLS) starts from a powder material, which also acts as the supporting material in this process. Polyamide (PA) is mainly used for SLS. Compared with FDM and FLM, sintering achieves better layer bonding and higher resolution, which is enabled by the particle size and laser process. FDM/FLM on the other hand offers a wider choice of materials and more degrees of freedom than SLS. If global material consumption is considered according to the form of presentation in the additive manufacturing industry, according to the Wohlers Report (2014), the following result emerges:

- 43 % resin (process group UV curing);
- 31 % filament (process group extrusion);
- 26 % powder (process group sintering and binder technology).

The material market is clearly dominated by the process group UV curing. This is the result of two factors: first, this process group comprises the systems that have been established on the market longest; second, the UV systems in many cases require a large amount of material for the manufacturing process. The global market for equipment for additive manufacturing (based on the number of systems sold) is distributed among the manufacturers as follows [1]:

- 55 % Stratasys Ltd., Eden Prairie, Minnesota, USA;
- 18 % 3D Systems, Inc., Rock Hill, South Carolina, USA;
- 11 % EnvisionTec GmbH, Gladbeck, Germany;
- 3 % Mcor Technologies Ltd., Dunleer, Ireland;
- 2 % EOS GmbH Electro Optical Systems, Krailling, Germany;
- 2 % Beijing TierTime Technology Co., Ltd., Beijing, China.

The others are distributed among smaller manufacturers.

Accordingly, Stratasys, inventor of the FDM process, has sold with largest number of AM systems worldwide, and, with a 55 % market share, is the clear market leader. Lagging well behind (with 18 % market share) is the US company 3D Systems, which is regarded as the inventor of stereolithography (SLA). The sales price for FDM systems from Stratasys is between USD 9,500 and USD 500,000. The average sales price for industrial AM systems is around USD 90,370. A kilogram of thermoplastic filament for the FDM process costs between USD 250 and 500, depending on the grade. By comparison the price range for a kilogram of filament for FLM costs between USD 15 and 50 [1].

The "Trinity" of Part Requirements

Additive processes are increasingly becoming interesting for production, too. AM systems are traditionally used for manufacturing prototypes or sample parts. Thanks to the higher quality, faster manufacturing rates, and wider choice of material, the direct production of parts and products has increased its share of the overall AM volume (**Fig. 1**).

With a particular combination of part properties, it is particularly attractive to use additive manufacturing. Products or parts for which

- particular functions are to be integrated,
- individualization is provided, or
- the geometry is very complex because of the technical requirements

are predestined for production by AM systems under certain requirements. If there is a combination of these three properties, an additive process may be the only possibility for manufacturing the envisaged part. Integration of functions in parts manufactured by selective laser sintering can only be carried out via

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Fig. 2. Autonomous robots with pneumatic bellows actuator as drive. Printing of the actuators saves assembly operations and reduces the gripper weight (figure: Fraunhofer IPA)

Fig. 3. "PeanLight" lampshade with graffiti design. A peanut formed the model, which was digitized to provide the guideline for additive manufacturing (figure: Fraunhofer IPA, Jeroo)

design measures. Achieving this presupposes at least a basic knowledge of the SLS process.

A well-known example of the successful integration of functions in laser-sintered parts is the pneumatic bellows actuators that have been developed at the Fraunhofer Institute for Manufacturing Technology and Automation IPA in Stuttgart, Germany, and completely manufactured by SLS. From the approach of 3-D-printed pneumatic actuators, Festo AG & Co. KG, Esslingen, Germany, developed a bionic handling system that received the German Future Award in 2010 (**Fig. 2**). A significant economic advantage of the printed actuators consists in the fact that assembly steps can be saved. In addition, this technique allows the weight of the gripper system to be reduced (compared to classical systems).

By comparison, the "PeanLight" lampshade impressively illustrates how products can be individually personalized. The customer himself sends in an object he has chosen himself as model, in this case a peanut. This is digitized by means of a 3-D optical scanner. The data are subsequently processed, scaled up and functionally extended. The laser sintering unit subsequently produces the product in a lot size of one. In an additional individualization step, the lampshade produced by additive manufacturing can be further decorated by a graffiti artist (**Fig. 3**).

Probably one of the biggest advantages of additive manufacturing processes is the possibility of producing complex geometries such as are not possible with any other manufacturing process. The complexity that can be achieved with these parts is illustrated by the "Simus" robot fish. All the housing parts and attachments, such as fins and stabilizers, are laser sintered in a 3-D-structured packaging housing, which protects the robot kit for shipping and contains all the necessary parts, in a similar way to a surprise egg.

The packaging housing also has a process-related function. In the case of SLS, this is a powder-based process. Regions of the powder bed that do not belong to the part serve as supporting material. After the construction process, the parts must be taken out of the loose powder and freed of residual powder. The packaging housing performs the function of preventing the loss of small parts while at the same time protecting the parts against damage during powder removal (**Fig. 4**).

Variations with Hollow Structures and Endless Fibers

Because the process is so adaptable, the FDM and FLM processes offer other interesting possibilities that would be difficult to achieve with any other additive process. In the case of FLM, path planning is performed at every layer of the part, ultimately resulting in a specific G-code. This path planning in the layer consists of paths, which represent the contour of the part in the respective layer, and of a "filling strategy" for the interior of the part. With FLM, various filling strategies, such as honeycomb structures, are possible. With FDM, only 45° hatching is used. Hollow structures without supporting material can be generated directly with the G-code with the aid of the paths of the filling strategy, without generating them in CAD. This effect is caused by the variations in the spacings between the individual paths. In this way, the material consumption, the manufacturing times, and thereby also the costs, can be reduced. In addition, lightweight design structures

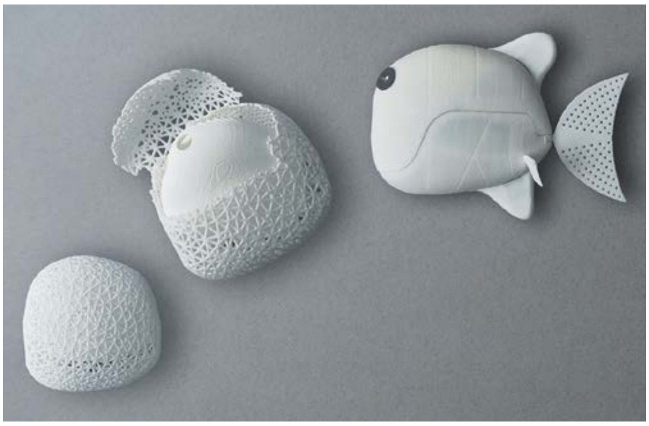

Fig. 4. Simus robot fish: from the egg to the fish. All parts are laser sintered in a 3-D-structured packaging housing and are thereby protected against loss and damage (figure: Fraunhofer IPA)

Fig. 5. Filling strategy with 45° hatching: depending on the design, it allows solid filling or a hollow structure to be produced (figure: Fraunhofer IPA)

can be generated that are not possible with any other process (**Fig. 5**).

An essential advantage of FLM is the high material bandwidth that can be processed. Besides materials with different pigmentation, filled thermoplastics, e.g. polycarbonate with nanotubes, can be used for 3-D printing. It is also possible to integrate endless fibers in a controlled way into the parts. Possible fiber materials include carbon, glass and Aramid. With a nozzle diameter of 1 mm and 1-component rovings, approx. 10 % fibers can be achieved in the part produced by additive manufacturing.

In the approach taken by the "3D Fibre Printer" (**Title figure**), which was developed at the Fraunhofer IPA, fiber integration is solved with a special FLM nozzle. The fiber roving is introduced into the nozzle from the side, wetted by the thermoplastic melt and transported. This fiber-matrix extrudate is then deposited in layers, in the manner typical of FLM, in order to generate the part. In contrast to this, the Mark One (manufacturer: MarkForged, Inc.) uses a thermoplastic filament with integrated endless fibers directly. The handling is therefore significantly simpler with this system. However, the 3D Fibre Printer shows greater system variability.

Multicomponent Parts and Integrated Components

Different thermoplastics can be combined to produce multimaterial parts. This is another striking advantage of the FLM process. Producing for a complex 2-component part requires a printer with three extruders: one extruder for each of the model materials that have to be combined and one extruder for the support material, which must be compatible with both model materials. In principle, more than two model materials can also be used, as long as there is sufficient adhesion between them and the support material. In mid-2015, Agor GmbH, based in Hörselgau, Germany, opened an additive manufacturing center at its Bietigheim-Bissingen site in Germany, with the focus on robot-based processes. The FLM systems developed there are designed to use various commercial or series thermoplastics. The system also allows different types of Desmopan (TPU, manufacturer: Covestro AG, Leverkusen, Germany) to be processed (**Fig. 6**).

Another interesting aspect of FDM and FLM is the fact that components can be integrated into the part during the manufacturing process. For the purpose, a spacer must be provided in the part itself. The build-up process can then be paused as required, the component inserted and integrated by the further application of thermoplastic layers. This manufacturing strategy, a development by the Fraunhofer IPA, is sold under the name "Pack FLM" (PFLM). A robot axis-system is most suitable for PFLM, since this offers the highest degree of freedom. The PFLM strategy permits components of different materials, including metal, to be integrated in the additively manufactured product without an assembly step. In this way, entire semi-finished products, including electronics or other products can be incorporated into the part, and functions thereby integrated (**Fig. 7**). »

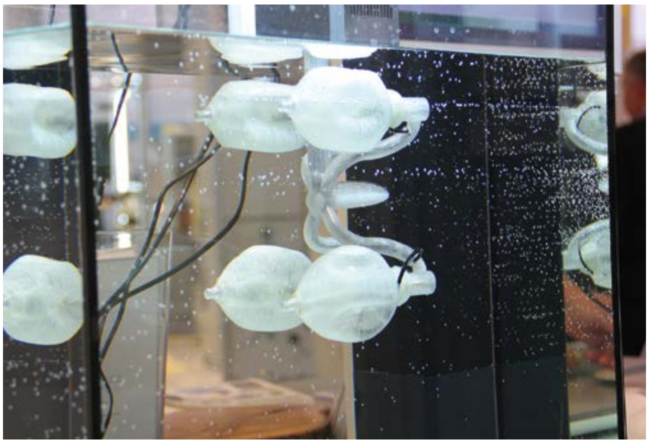

Fig. 6. Fourfold Oktopus submarine drive (OSA). The assembly is manufactured in a multicomponent process from PC and a TPU (figure: Fraunhofer IPA, Covestro)

Fig. 7. LED and optical waveguide integration with PFLM. By interrupting the layer build-up and placing an insert, the various components can be integrated without an assembly step (figure: Fraunhofer IPA, Covestro)

Special Strengths: Production "on Demand" and Small Series

Two areas in which additive manufacturing shows advantages in general are in production on demand and small series, in which an injection mold is not worthwhile. One example of production on demand is spare parts for Segways. In the particular case, this is the coupling of the electrical vehicles. It consists of two ABS parts and a TPU connector. The parts transmit the torque of the electric motor to the gearbox. Two sets are required per Segway. The coupling on this vehicle is one of the parts with the highest wear. The purchase price and availability period were the key arguments for Sewato, Blumberg, Germany, to consider on-demand production by means of FLM, and thereby to replace classical stockholding. Several test vehicles have since been equipped with additively produce coupling sets at Sewato. They have so far covered approximately 3,000 km without any apparent wear.

The possibilities offered by additive manufacturing for small series can be illustrated with the example of drafts by design students from Schwäbisch-Gmünd, Germany. In a one-week workshop, the students were asked to develop storage furniture based on semi-finished products such as wood panels or corrugated cardboard, together with additively manufactured connecting elements. One of the goals was that, despite the additively manufactured elements, the product should have an acceptable manufacturing price and thereby be producible in small series. With this aim, the connecting elements had to be designed in a targeted way using process know-how. Besides the design of the actual parts, the strategically best placement in the manufacturing space of the FDM machine also had to be defined (**Fig. 8**). All 13 designs by the students could be manufactured and fulfilled the specified criteria. In an exhibition in early 2015 at the Fraunhofer IAO, the designs were shown to the public. The example very clearly shows how quickly people can be made familiar with the topic of additive manufacturing and enabled to make products with these systems.

Summary

To sum up, thermoplastic-based additive processes hold high potential for abandoning the classical approach to rapid prototyping. However, there are important points, such as integration into production lines or quality assurance, that are still not mature. Topics such as surface quality and reducing the manufacturing time have also not yet been satisfactorily solved. ■

Fig. 8. Storage box of wood panels and FDM connectors. In a design study, semi-finished products are joined using additively manufactured connectors (figure: Fraunhofer IPA, HfG Schwäbisch Gmünd, Straub Verpackungen)

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