Finer, Bigger, Faster

What Additive Plastic Manufacturing Can Do. The View of a Full-Service Provider

Production is becoming ever more flexible, diversified and decentralized. Without doubt, additive manufacturing processes make a crucial contribution to this, also initiating the transformation from production-based design to design-driven production. In this article, the 3D printing service provider FIT outlines a best-practice panorama of current technologies.

The biggest ever 3D-printed lattice structure was assembled along over 2000 precisely fitting joints into an 8 m-high retable © FIT AG/Lisa Kirk

Wohlers Report 2021 on the economic analysis of additive manufacturing contains, in highly simplified terms, two messages, one good and one bad. First, the good: additive manufacturing is on trend. Globally, the industry reached a value of almost USD 12.8 billion in 2020. On the other hand, the growth of the industry in the Covid-19 age fell from 27.4 % (2019) to 7.5 % (2020). The shifts within the industry are interesting: while the majority of the machine manufacturers in 2020 had to accept an appreciable decline in sales, the 3D printing service providers notched up sales growth from 7.1 %, which corresponds to approx. USD 5.3 billion in this segment.

The fact that the industry's interest in 3D printing in recent years has crystallized in high investments in systems is now backfiring. The capacities built up should deliver successful products, but industry is still having difficulties in getting things moving. The advantages of additive manufacturing, such as freedom of design, functional integration, rapid availability, exorbitant lightweight engineering and more agile production are convincing as a response to the growing pressure for progress. Nevertheless, even now, 30 years after the invention of 3D printing, a clear chasm is apparent between euphoric expectations and sensitization to the actual effort required to master the technology.

"Additive manufacturing is one of the most complicated technologies that exist at present. Building up true know-how takes at least five years. You must be willing to invest this time," estimates Carl Fruth, CEO of FIT AG. Finally, the complete process chain must be adapted to additive

Fig. 1. Console box for the Toyota LQ, manufactured in several individual parts using laser sintering (SLS), and carefully finished © FIT AG/Lisa Kirk

manufacturing. This starts with the systematic changeover to a specifically additive design, requires a machine inventory that does not limit the projects to the available equipment, and a considerable infrastructure for post-processing and quality assurance. Those wanting to shorten the lengthy learning process take advantage of the know-how of service providers. "Now's the time for specialist," says Fruth, confirming the Wohlers analysis.

FIT AG is one of these service providers, offering all-round service on all aspects of additive manufacturing. Interposed between machine manufacturers, industrial clients and service providers, the company, with over 25 years of experience in project business, has an extensive manufacturer-independent technology portfolio, and extensive expertise in pre- and post-production (engineering and process development, post-processing and quality assurance). At FIT, R&D takes a high priority, by validating new materials, developing new technologies for industrial use, through to test operation of alpha machines, as well as participating in numerous research cooperations. This expertise gives rise to the following overview, as a best-practice panorama of current technologies.

Individualization and Part Size Require Joining Processes in Laser Sintering

One of the best mastered and most widely established plastics processes is the laser powder bed fusion technology of selective laser sintering (SLS). Here, polyamide powder is heated to slightly below the melting point and selectively bonded by a CO_2 laser. The layer thicknesses are approx. 100 to 120 µm (e.g. EOS P 730, P 760). SLS, with its traditional materials such as PA11, PA12, PA-GF, alumide, TPU2 and PA2241 FR, is in widespread demand for prototypes, but also series plastic parts. The latest systems aim for a significant performance increase; thus, the EOS P 500 applies polymer powder at a record rate of up to 600 mm/s onto the build platform.

A disadvantage in SLS so far is the size limitation due to the build chamber. Larger parts must be assembled from several individual parts. Furthermore, the industrial high-strength joining of individual SLS parts, e.g. to mass-produced injection molded parts, is highly interesting for pursuing the trend toward customization. To achieve these goals, downstream joining processes for SLS parts are necessary. Here, the best bond properties, stable and media-tight, are offered by welding, rather than adhesive bonding or screwing; the interactions of this process with the SLS part are thoroughly researched in the FAB-Weld [1] research project. The differences to the welding process here, compared to conventional parts, can be attributed to SLS-specific influencing factors.

The complex structure, as well as the changed absorption and flow properties of the SLS parts, lead, e.g. in the infrared welding process, to changed joint characteristics, which must be taken into account in the process design. For a downstream IR welding process, the build-up direction of the SLS parts must be observed – in particular oblique placement in the build chamber has an unfavorable effect on the heating behavior because of increased surface roughness and a possible staircase effect – whereas vibration welding is largely independent of the build-up direction.

Due to manufacturing criteria in the SLS process (e.g. weld-optimized build-up direction) and adjustments to the welding process control (e.g. heating time), high-strength bonds are also achievable between SLS parts as well as in combination with injection-molded parts, with the welding seam strength in the region of the base material. "Vibration welding comes out slightly better for bonds between compact SLS solid material parts, while infrared welding should be preferred for thin-walled SLS structures because of the lower mechanical loading during welding," summarizes Michael Wolf of the Department of Plastics Technology (LKT) at the University of Erlangen-Nuremberg, Germany. »

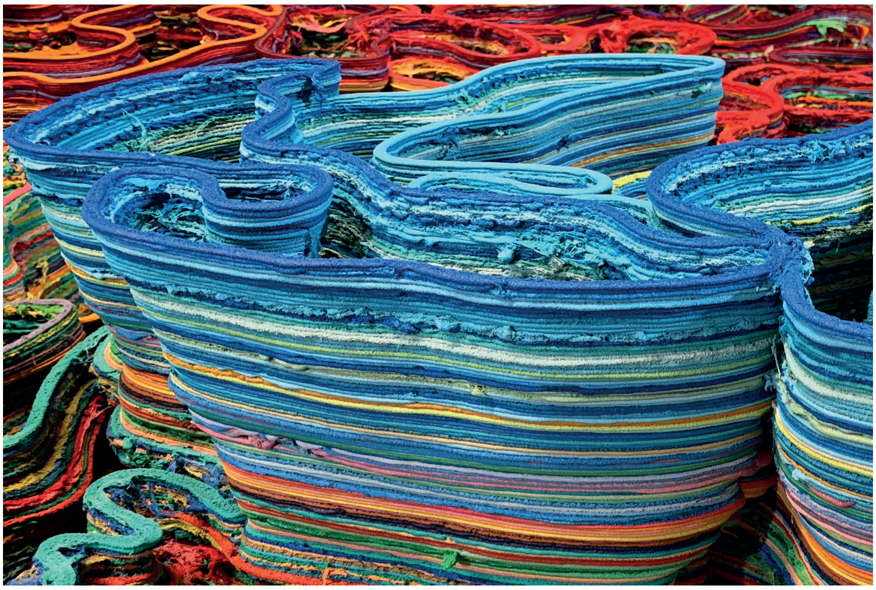

Fig. 2. Detail of the sound-absorbing 3D sculpture, created by the robotic FDM process © FIT AG/ Oliver Cynamon

Fig. 3. Accomplished advertising sculpture for L’Oréal with GDP corpus, generated by photopolymerization of a highly-viscous gel © FIT AG/Lisa Kirk

Fig. 4. SLA craniofacial model as preparation for surgery © FIT AG/Lisa Kirk

An example of a real industrial application of SLS components is the futuristic design of the free-standing console box with integrated touchpad in the new Toyota LQ (**Fig. 1**). The engineering team has performed a manufacturing-optimized lightweight redesign of the geometry and the internal structure, taking into account the standards and design guidelines specified by the Toyota Motor Corporation. The material used was PA 2241 FR. With a dimension of 1200 x 250 x 480 mm, the model was divided into eight geometrically appropriate individual components. The quality of each individual element was verified by several tensile tests. The design alternatives were subject to FEA analyses for digital simulation of the forces acting on them while the vehicle is in use. The design was finally validated in a test production to verify the functionality of the customer-specific holders for optimum welding and mounting.

FDM Variant with Pivoting Robot Arm

The notion of 3D printing has been most lastingly shaped by the FDM (fused deposition modeling) process. Plastic filament of dimensionally stable thermoplastics is heated in an extruder head and applied in layers onto a build platform. An interesting update to this principle is represented by “robotic FDM,” in which the extruder is mounted on a swiveling robot arm, so that significantly larger objects are possible depending on the action radius. As material, a wide spectrum of plastic pellets are suitable; gentle material change, e.g. from glass fiber-reinforced ABS to polycarbonate, can be implemented. However, the price of this versatility is a high technical effort for the process development, since basically for each project a separate manufacturing process must be specified with its own process parameters (adjustment of temperatures, modification of build-up rates, etc.) based on the desired material.

An example of the individual solutions that require a project with robotic FDM is the “silent orchestra” art object with sound-absorbing function by the artist Peter Lang (**Fig. 2**). In order to obtain uniformly parallel layers in the entire bionically inspired object, a special algorithm had to be programmed, with which the robot arm can describe a path over the entire build surface of 6 x 3 m without material overlaps. The material had to satisfy multiple requirements, with criteria such as sustainability, a fibrous consistency for sound absorption, good pigmentability, flame resistance and, of course, general suitability for material extrusion. With Arboblend (manufacturer: Tecnaro), a biocompatible plastic was chosen for almost CO_2-neutral manufacturing, which was transformed into a colored pellet stock with the aid of beer as a natural adhesive and high-quality pigments from Pigment Kremer [2].

Fig. 5. In the PolyJet process, parts like the taillight and gear lever shown here can be produced in full color, translucent or with textures in high detail resolution © FIT AG/Lisa Kirk

Dimensionally Stable Hollow Articles up to 1.80 m High through GDP

The relatively new gel dispensing printing (GDP) from the Israeli company Massivit works in quite a similar way to FDM, here a highly viscous gel (Dimengel, a proprietary white acrylic-based photopolymer) is applied layer by layer from an extruder and cured with UV light. With GDP, virtually any geometries can be produced as dimensionally stable hollow bodies and without support structures, at rapid build-up rates of 2 kg material per hour up to a height of 1.80 m in one piece. The components are lightweight and flame resistant acc. to DIN 4102 – class B2 / ASTM D635 / UL 94 HB.

The strength of the process is shown by the example of a large advertising sculpture for the product launch of a new face cream from L'Oréal (**Fig. 3**). At the press conference, the product was to be displayed in an attention-grabbing way. To keep the time-to-market as short as possible, a production-ready 3D data set was produced by reverse engineering in only one week's time; the object was then printed in three individual pieces, assembled to its full size of almost 1.80 m and elaborately finished by specialists.

Huge Color Palette for 3D Printing with Photopolymers

The established inventory of plastic part manufacturing includes stereolithography (SLA), the oldest 3D printing process, in which a thermoset synthetic or epoxy resin is cured by a UV laser (**Fig. 4**). The post-processing work includes support removal and, if needed, curing by UV light. SLA generates highly isotropic parts that have a very high detail resolution, accuracy and very smooth surfaces (Ra ≈ 2 µm). The layer thicknesses are 25 to 30 µm (e.g. with ProX800 or ProX950 from 3D Systems) and even 10 µm for high-strength functional parts with the Figure 4 printing system from the same manufacturer. For SLA, proprietary high-performance polymers such as Accura Xtreme White 200, Accura ClearVue or Accura HPC are used, for Figure 4, a specific material spectrum is available with Tough-Gry 10, MED-AMB 10, and many others.

In the PolyJet process, on the other hand, a printing head applies liquid photopolymer layer by layer directly onto the build platform; curing is performed by UV light. It can be used to produce parts with a very fine layer thickness from 14 or 27 µm respectively and a dimensional accuracy of ± 0.1 % with extremely smooth (Ra ≈ 6 µm), non-porous surfaces. The parts can be used immediately as real end-use products. The special feature of this process is that parts can be produced fully colored, translucent or with textures in high detail resolution; several materials with different properties (e.g. different degrees of hardness) can be mixed in one operation (**Fig. 5**). Thus, over 500,000 color shades are available on the Stratasys J750 3D printer. Via the Capps.it additional service, color trueness can be ensured via a calibrated color management.

One example from the medical field is eye prostheses (**Fig. 6**). In a pioneering research project [3], a process is being developed for providing highly realistic and accurately fitting "glass eyes" in individual series production. With additive manufacturing, the manufacture of a high-tech eye prosthesis takes only a few hours instead of approx. 24 weeks, which means a huge relief for the patient. Additive manufacturing is also ideal for quality of the artificial eye, since each iris has a unique pattern of furrows, stripes or spots. Full-color PolyJet printing in particular is capable of manufacturing the realistic copy of an iris from biocompatible photopolymers, with an astonishing impression of three-dimensional depth,

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References & Digital Version

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Fig. 6. Highly realistic eye prostheses from a full-color PolyJet 3D printer © FIT AG/Steffen Galster

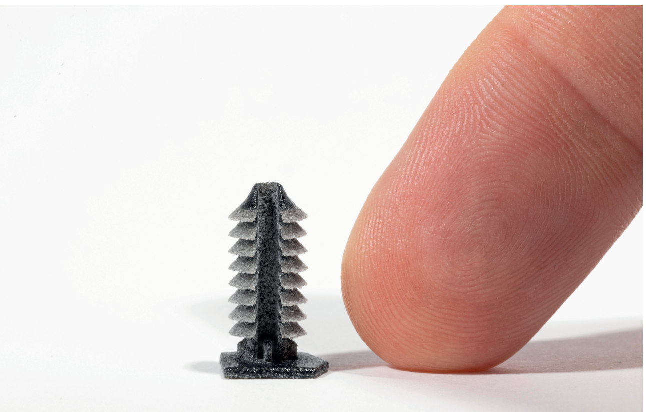

Fig. 7. Fir-tree clips with elastic lamellae, manufactured by using the SAF process © FIT AG/Steffen Galster

with opaque and transparent parts and a lifelike texture, including the appearance of fine veins on the eyeball.

Extremely Fine Geometries by the SAF Process

In the binder jetting process, finally, a print head applies a liquid binder onto a layer of plastic powder, which bonds the affected regions. The ultimate strength of the parts is achieved by means of a downstream heat treatment. The layer thickness is around 150 µm (e.g. Voxeljet VX800 and VX500). The binder jetting principle is versatile and is also used for processing material classes other than plastics, for example ceramic printing and selective cement activation.

An interesting upgrade in the field of plastics is the new SAF technology from Stratasys (selective absorption fusion). In this, an infrared-absorbing liquid is selectively applied on the polyamide powder bed. PA11 is used for this. The maximum part size here is 315 x 208 x 293 mm (Stratasys H350); the layer thickness is 100 µm, so that homogeneous polyamide parts can be obtained in industrial quality, even with extremely small, fine geometries (**Fig. 7**). The process aims to be competitive with injection molding and to allow bigger lot sizes. The high recycling quota of the material (70 % acc. to the manufacturer) is also interesting.

How Additive and Conventional Processes Complement One Another

Injection molding for series manufacturing is often seen as the benchmark for measuring the productivity of a process. "That may well be acceptable as an ambitious metric. However, hoping to make the same part less expensive through additive manufacturing is an unrealistic desire," explains Carl Fruth. "Transferring the technical expectations from injection molding to additive manufacturing is the problem of old wine in new skins." It is not the aim of additive manufacturing to replace conventional processes, but its added value lies in complementing the existing manufacturing spectrum and shifting the boundaries of what is technically feasible. Additive manufacturing can by all means optimize injection molding, for example by manufacturing improved injection molds with laser melting instead of milling and turning.

More recent approaches in additive manufacturing are aimed at a combined, simultaneous manufacturing of both mold tool and part, for example to manufacture complex, very soft silicone parts with a Shore hardness of 25 A that have not yet been feasible with any other methods. Such a process is currently being industrialized at FIT.

How additive engineering and manufacturing, and additive and conventional methods complement one another can be seen by the example of a filter carrier, which helped FIT to bridge the interrupted delivery chains in full-face coverings at the beginning of the Covid-19 pandemic. The typical form of the filter carrier was constructed in just a few days; prototypes for ergonomic optimization of the plastic (PA12) molding were manufactured by using SLS . From the final prototype design, mold inserts were manufactured by

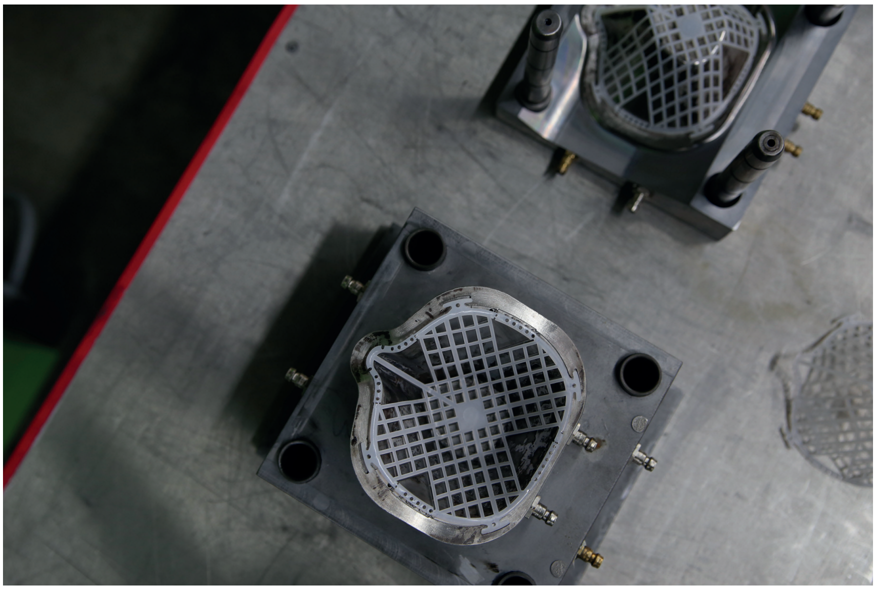

Fig. 8. Filter basket of PE in the injection mold, with a mold insert manufactured by laser melting © FIT AG/Lisa Kirk

Fig. 9. The leg of the designer table consists of 60 laser-sintered individual parts that were welded together © FIT AG/Lisa Kirk

Fig. 10. The ornamental lattice geometry of this table was created by using stereolithography © FIT AG/Lisa Kirk

laser melting with steel powder, which allowed for an output of up to 30,000 filter baskets per day (**Fig. 8**). The final material of the injection-molded parts was PE.

From Production-Determined Design to Design-Driven Production

To make an interim summary: the technology spectrum of the manufacturing processes proves to be differentiated and – with the corresponding know-how – can be readily mastered; it now fulfills comprehensive product requirements, for example relating to large formats or a fine resolution. However, the quality of the results ultimately stands and falls by the quality of the engineering, since the paradigm change from production-determined design to design-driven production is characteristic.

Additive engineering must fulfill a variety of tasks. Product requirements such as functional integration and lightweight design meet requirements for manufacturing-oriented and process-specific design, efficient use of material through topology optimization, efficient packing of series parts in the build chamber, downstream costs for post-processing, which must be kept as low as possible, and an overall short development time. Time and costs can be saved here through digitization and automation and the use of suitable software tools, as is described by the design and construction expert for additive manufacturing Antonius Köster: "Lattice structures, generative design, structural optimization and simulations are ever increasingly to be found in the development departments. I venture a look into the crystal ball and predict that, in the future, with software, materials and the suitable processes, we will be able to design product properties that used to be unimaginable. Material transitions, for example, will be designed at the computer, checked by simulation and transferred directly to the build processes."

Thus, it will be possible to perform design iterations with different focuses (costs, functionality, quality parameters) faster and more economically. Examples of powerful software tools are Netfabb Simulation, Altair Hyper Mesh, Autodesk CFD, Frustum, solidThinking Inspire, Elise or Autodesk Nastran.

Computational Engineering for Design Automation

To limit the high development costs of additive manufacturing, computational engineering provides interesting solutions for digitizing the design process of technical products through automated construction solutions and smart algorithms. The role of the designer is transforming into that of a programmer. Automatically generated design variants can be quickly and easily compared from the points of view of taste, function and cost. For example, it can be immediately seen how a particular parameter change affects the manufacturing costs.

The influence of technology, material and algorithm on the design of the end-use product can be seen in the following comparison of 3D-printed bar tables, which were designed with algorithms chosen according to the process. To realize the geometrically complex structure of the SLS table (**Fig. 9**) in the required height from PA12, it was manufactured in 60 individual parts and accurately welded together. The complex three-dimensional rosette structure was generated in rotational and mirror symmetries from regular rhombic elements by "Penrose mapping." Each individual part is a variant on the basic form.

For the ornamental lattice geometry of the SLA table (**Fig. 10**), the principle of "box morphing" was used, an efficient alternative to the CAD approach to geometry modification. The outer geometry is fixed, a basic design form is packed into a box as a frame, the boxes are morphed onto the entire form of the table and the geometry is mapped into the "warped" box. This permits very complex geometries, which are easy to handle, though. The data set for the table has a very high resolution, which can only be achieved and processed on high-performance computers with the aid of expert algorithms.

The special feature of the design of the GDP table (**Fig. 11**) lies in the "overhang evaluation," since the entire body is conical, consisting of bubble motifs becoming ever larger towards the top. The closing lid, built completely without supports, is virtually at a 90° angle at the contact point. The entire object was printed in only two hours; the 2 mm skin was filled with foam for stabilization. In a careful finishing procedure, the corpus was decorated with a high-quality bronze coating, so that the table has the look and feel of bronze, is weather resistant and also ages like »

Fig. 11. The entire object was printed via GDP as a hollow article, filled with foam and coated with bronze © FIT AG/Lisa Kirk

Fig. 12. Designer table manufactured by using robotic FDM © FIT AG/Lisa Kirk

bronze, but is significantly more economical to manufacture than a bronze casting.

The bar table manufactured with Robotic FDM (**Fig. 12**) was designed by using "design layer tweening". The three key layers of base, center and upper edge were defined, and all other layers between are automatically built on this, in a natural, organic flow.

Pushing forward Post-Processing Steps or Automating them?

Process optimizations also start with the post-processing effort. In general, this is kept as small as possible in order to minimize manufacturing costs and times. In all processes that require a support removal, it is one of the tasks of engineering and data processing to keep the effort for this as small as possible from the start. Technical approaches attempt to bring forward post-processing steps into production or to automate the support removal. This is countered by efforts to increase the production-related part quality with additional processing, e.g. heat treatment (HPHT, high pressure heat treatment) or electromechanical smoothing (Hirtisation, a process patented by the Austrian specialist Hirtenberger Engineered Surfaces).

But also challenges to standard methods, such as joining, become greater with increasing complexity, as shown, for example, by the sacral art work of Altmühldorf, Germany. For the redesign of the sancturay, a spectacular, delicately structured retable was manufactured [4]. Because of its dimensions (8 x 2.50 m), the biggest ever 3D-printed lattice structure so far was manufactured in over 60 individual parts from PA12 by using SLS, which then had to be seamlessly bonded together into a perfect whole at over 2000 precisely fitting join points (**Title figure**).

How post-processing can economically add up with manufacturing is shown by the metal coating process. By electroplating, plastic parts can be finished in a way that, apart from the metals look, they also gain actual mechanical and electric properties of metals, such as long-term stability, strength and stiffness, electrical conductivity and electromagnetic compatibility. The target geometry for a homogeneous layer thickness is ±20 µm for nickel and copper. If, for example, an SLA part is coated with nickel (150 µm), the properties of carbon can be obtained. A good example of the economical compromise between perfect surfaces and throttled production costs are parts for aerodynamic tests in the wind tunnel, such as the nickel-plated SLA brake thruster (**Fig. 13**).

Quality Assurance Systems throughout the Value-Creation Chain

However, the topic of quality is key to any manufacturing optimization and all efforts aimed at efficiency increase and cost reduction. The value-creation chain of additive manufacturing must be safeguarded by a clearly defined quality assurance system, which provides for a comprehensive spectrum of destructive and non-destructive, process-dependent methods at all points in the process chain – before, during and after manufacturing. This obviously serves to fix the customers' confidence in the new processes, but at the same time, quality evidence has become a basic prerequisite for passing the approval processes that are now necessary particularly for real end-use applications.

Examples of mandatory industrial standards include the general quality standard ISO 9001 with e.g. FMEA or 8D Reports, KVP and Kanban, ISO 9100 for aerospace, ISO 13485 and FDA Compliance for medical products, as well as TISAX (Trusted Information Security Assessment Exchange), a standard for in-

Fig. 13. SLA brake thruster nickel-plated by metal coating © FIT AG/Lisa Kirk

formation security defined by the automotive industry. With material developments, too, industry-specific certifications play an important role, e. g. the fire-safety certifications of materials Ultem 9085 (a PEI) and Antero 800NA (a PEKK) for the bus and rail sector acc. to EU standard 45545–2 or the biocompatibility and food-contact approvals for the material Ultem 1010 (also a PEI, manufacturer Stratasys in each case) taking into account the NFS-51 standards and the guideline ISO 10993/USP Class VI.

Additive manufacturing, in its current stage of development, makes production more flexible, diversified and decentralized. "Additive manufacturing of plastics is increasingly gaining in importance. [...] A highly dynamic development of new materials and processes for additive manufacturing reinforces this trend," observes Prof. Dr.-Ing Dietmar Drummer of LKT in Erlangen-Nuremberg, Germany. Yet more attention has to be paid to topics such as sustainability for reducing the CO_2 emissions as well as the reuse or recycling of materials.

Artificial Intelligence on Its Way

Artificial intelligence is growing strongly and will replace trial and error with predictable results. The technical development here will be driven by two partly conflicting goals: increasing quality and reducing costs. "Despite all the efforts, I do not see a drop in prices in the near future," says Carl Fruth, dampening expectations. Nevertheless, as has also been shown by the litmus test of the crisis, the industry continues to head toward manufacturing of high-quality end-use products, such as series and spare parts. More and more real industrial applications from additive manufacturing can now be found throughout all verticals.

A key role here is played by the industry-specific certification of processes, applications and materials. The sectors of automotive engineering, motor sports, aerospace, mechanical engineering and energy, in particular, show great affinity for industrial 3D printing. As also noted in the Wohlers Report 2021, there is an increased focus on medtech. Individualization is one of the major megatrends today and is leading to a dynamic demand for tailor-made series products.

Only Scratched the Surface So Far

The industry that is mostly getting off to a good start is currently architecture and building. Materials such as cement-like Econit and geopolymers promise new perspectives for additive manufacturing. "The additive manufacturing industry has never been more exciting. Entirely new types of products are being designed for AM and introduced regularly as a result of the technology. Even so, the adoption of AM for series production has only scratched the surface of what is possible.," explains the AM expert Terry Wohlers in the interview, adding: "In the future, we can expect it to exceed USD 1 trillion, but a great deal of work needs to be done across most industrial sectors before this can occur." ■