

An example of additively manufactured two-component functional parts – produced completely without assembly – is planetary rollers made from TPU and PHA

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## Droplets to the Beat of Milliseconds

### *Arburg Plastic Freeforming: Current Investigations on Part Optimization*

Arburg Plastic Freeforming (APF) is based on qualified original materials in the form of plastic granulates as used in injection molding. Current researches illuminate influences on the resulting part quality of this additive process. Because the open system permits adaptation of the parameters, the mechanical and geometric properties of the parts can be optimized in a targeted manner. In this way, tensile strengths and part densities comparable to those of injection molded parts can be achieved.

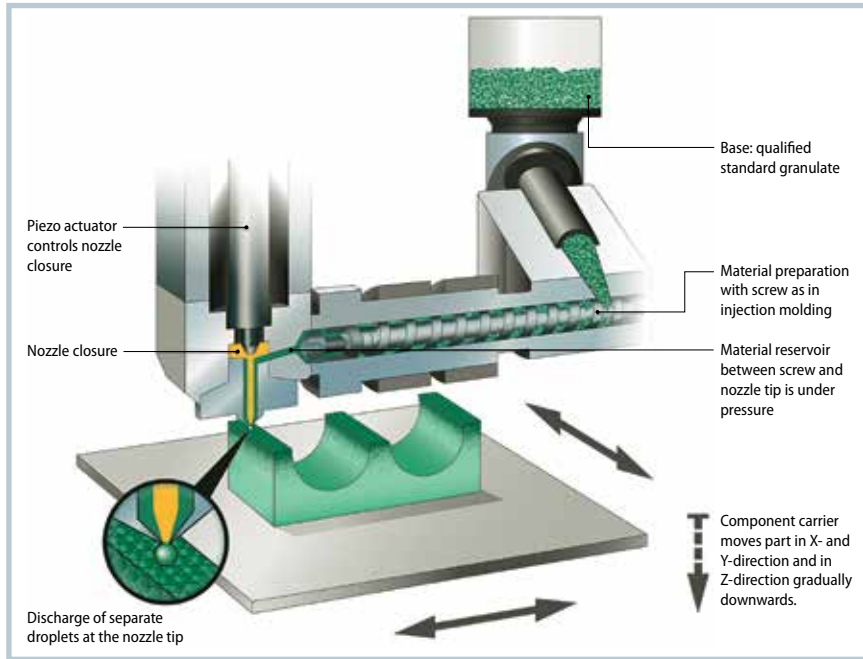
In addition to prototyping, Arburg Plastic Freeforming (APF) is particularly well suited for industrial additive manufacturing of functional parts. Custom-made plastic parts for consumer goods, medical implants and spare parts made of the original material are only three of the many areas for which the APF-machine (Freeformer) is predestined. The technology offers great freedom in terms of materials and is able to process plastics with melting points up to max. 350°C. In addition to standard materials like ABS, PC and amorphous PA more materials can be successfully processed on the Freeformer, such as TPU and other thermoplastic soft materials. Moreover, initial results with re-

gard to the processing of semi-crystalline materials such as PP are available.

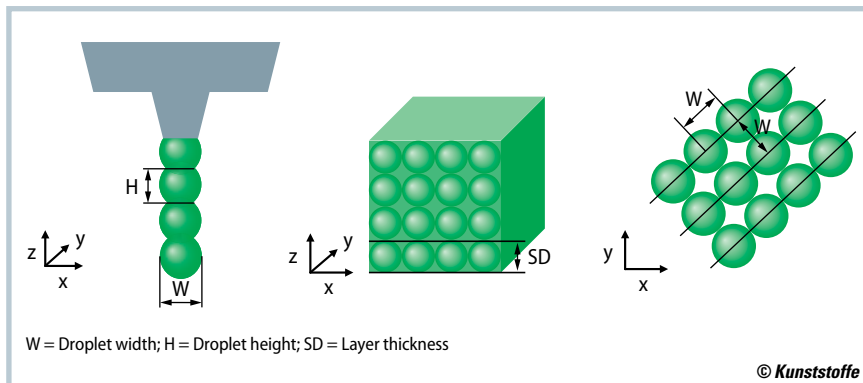
The APF process begins – as in injection molding – with plasticizing of granulates via a heated plasticizing cylinder featuring a 15 mm screw. Next, a stationary high frequency nozzle closure discharges up to 240 droplets per second (**Fig. 1**). The droplets, which are generated under pressure, have a diameter of between 150 and 300 µm depending on the nozzle size and machine parameters. The smaller the droplets, the finer the surface texture, while larger diameters enable faster working progress.

The part carrier, which is movable via three axes, can be positioned in the X, Y

and Z directions and enables the precise placement of each individual droplet at the previously calculated position. The applied droplet bonds with the existing surrounding material so that, layer-by-layer, three-dimensional parts with a high mechanical strength are produced. The discharge quantity depends on the set droplet volume and applicable frequency. For the 0.2 mm nozzle diameter, it is up to 25 cm<sup>3</sup>/h. The layer thickness also depends on the applicable nozzle diameter and can currently be between 0.15 and 0.30 mm. The Freeformer is equipped with two discharge units as standard. The build chamber, which can be heated from 50 to 120°C, provides space for »



**Fig. 1.** The APF process is based on plastic granulates. The qualified original material is melted in a plasticizing unit and discharged via a nozzle in the form of droplets (© Arburg)



**Fig. 2.** The droplet geometry is determined by the nozzle size, the discharge rate per droplet and the flow properties of the material. Test cubes are produced to precisely set the aspect ratio ( $W/H$  ratio) (source: Arburg)

single or two-component parts, which are between 189 (1C-part) and 154 (2C-part) x 134 x 230 mm in size.

### Qualification, Selection and Preparation of Material

The aim of material qualification is to define the appropriate machine and data processing parameters for a specific material and part geometry in order to achieve the best possible part quality. The specified parameters can be changed individually at any time. Part quality depends on the material properties, machine parameters and data processing. All the parameters must be adapted to one another.

Standard plastic granulates can be used. The material should be as dust-free and dry as possible. To verify whether a new material can be processed, the correct processing parameters are determined in a standardized qualification process. Users can qualify their own materials or resort to Arburg's material database. Standard granulates such as ABS (type: Terluran GP 35; manufacturer: Ineos Styrolution), PA10 (Grilamid TR XE 4010, Ems-Chemie), PC (Makrolon 2805, Covestro), TPE-U (Elastollan C78 A15, BASF) and PP (Braskem CP 393, Braskem), are documented therein.

It also contains special plastics for specialized applications such as medical-grade PLLA (type: Purasorb PL18 and Re-

somer LR 708; manufacturer: Corbion or rather Evonik) as well as a PC approved for aerospace applications (Lexan 940, Sabic), for example. The range of qualified materials is continuously being expanded. In the Arburg Prototyping Center (APC) at the German headquarters in Lossburg, several Freeformers produce benchmark parts for prospective customers.

### Influence of Machine Parameters on Droplet Shape and Aspect Ratio

When a new material is to be processed, the temperatures of the plasticizing cylinder, nozzle and build chamber are adjusted to it. The bases for this are the details on the material data sheet. To keep part distortion as low as possible and to achieve good bonding between the droplets, the build chamber temperature should be as high as possible in the case of amorphous thermoplastics. It should, however, be below the melting point of the material being processed in order to ensure sufficient part stability during the process. Good droplet bonding is also achieved through high melt temperatures, but excessively high temperatures in the plasticizing cylinder can cause rapid material degradation. Further machine parameters include, e.g., dosing speed, back pressure and decompression.

In the next step, the size of the droplets is adapted to the target layer thickness. For the median nozzle diameter, this is 200  $\mu\text{m}$ . Changes in the discharge quantity per droplet and in the temperate influence both the droplet shape and the resulting part filling.

The droplet size can be changed through the use of nozzles of varying sizes and through a change in the specific droplet volume in the machine parameters. Selection of the nozzle size significantly influences droplet width; the selected droplet volume determines the droplet height. The droplet geometry is also influenced by the flow properties of the material. To achieve a good part density, the droplet height should be slightly higher than the desired layer thickness.

Depending on the resulting droplet thickness, the distance between two droplets is then adapted by means of the so-called aspect ratio (width-to-height ratio,  $W/H$ ) during slicing. To precisely set the form factor, test cubes are produced with different settings and then tested

with regard to their density and surface quality (Fig. 2). The additive manufacturing of the part will follow not before this result is satisfactory.

### *Slicing Defines the Layer Details*

During slicing, for example the parameters for positioning of the droplets on the part carrier are defined. Different strategies are employed for the outer contour and for the filling. The droplets of the outer contour are individually applied with high precision. For this purpose, the part carrier stops at each of the previously calculated positions. For filling the contoured layer, the part carrier moves along a defined path, while successive droplets are continuously discharged in rows. Thereby, the component density can be influenced by the distance between the individual drops. An overlapping of the filling with the contour can be defined in order, for example, to achieve better bonding of the droplets in the outer contour.

The scaling factor, which is adjustable in the X and Y directions, essentially depends on the specific material shrinkage. Dimensional stability in the Z direction, in contrast, is not only determined by the scaling factor, but also by the layer thickness. A further standard function included in the slicing software for the Freeformer is the automatic generation of a support structure adapted to the part. The result of material qualification is a specific profile with the relevant temperature, discharge and slicing parameters for the relevant material.

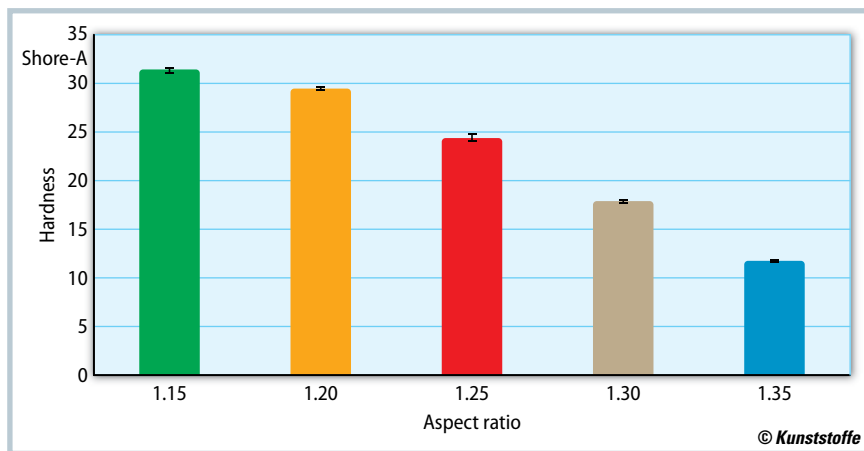
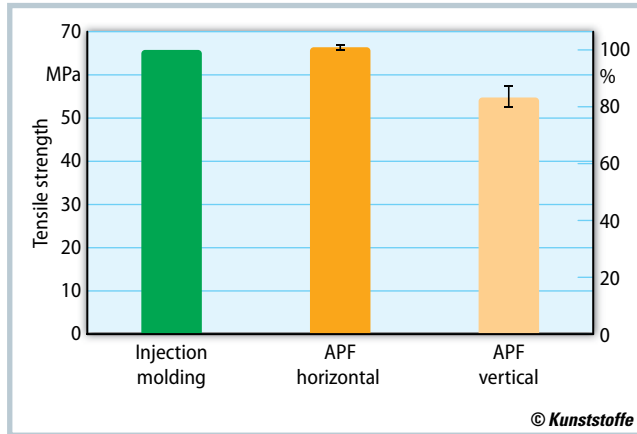
### *Influences of the Orientation during Layering and the Degree of Filling*

With the open system from manufacturer Arburg, the mechanical properties of parts can be influenced in a targeted manner. The influences of part orientation, part density and tensile strength of APF parts are shown below. Part quality is also compared with injection molded parts.

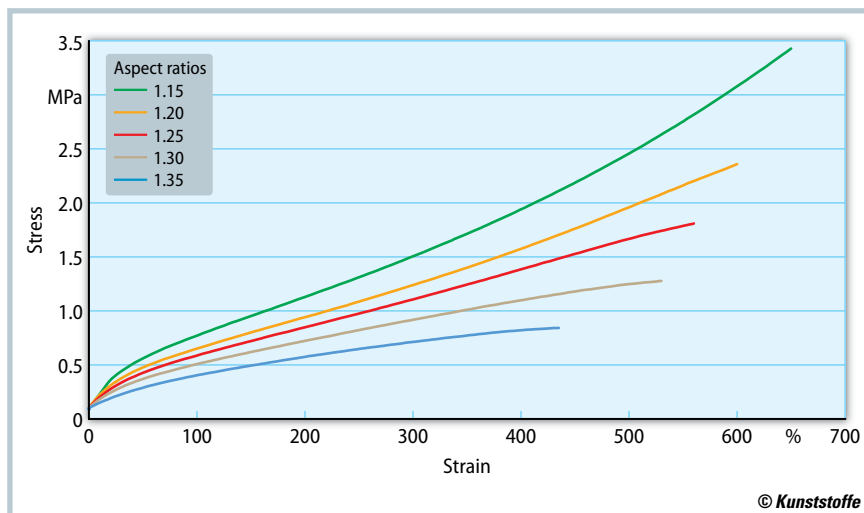
The orientation of the build direction along the axes has a significant influence on the mechanical strengths and therefore on part quality. For a test series, test specimens according to DIN EN ISO 251-2 (type 1BA) made from PC were built with identical process parameters in a horizontal and in a vertical orientation. The tensile strengths of horizontal build test specimens correspond to 100% to the maximum tensile strength. Owing to the layered structure, the tensile strength of vertically built tensile rods is lower. In this build orientation, around 83% of the strengths specified in the material data sheets were achieved (Fig. 3).

In order to achieve a high degree of part filling, the machine parameters together with the slicing parameters must be adapted to the existing material properties. The droplet size determines the layer thickness and the distance from the adjacent droplets. If these settings do not correspond, a high part density and accordingly high mechanical part properties cannot be achieved. »

**Fig. 3.** Compared to injection molded parts with optimized process parameters, achievable tensile strength of APF samples of PC (Makrolon 2805, 200  $\mu\text{m}$  layer height) are dependent on the build direction (source: Arburg)



**Fig. 4.** Different Shore A hardnesses can be achieved by changing the aspect ratios (W/H) with unchanged parameter settings (TPE: Medalist, specified as Shore A hardness 30) (source: Arburg)



**Fig. 5.** Stress/strain curves for tensile samples produced with different aspect ratios made from the material Medalist MD-12130H (source: Arburg)

By changing the aspect ratio (W/H), the density and therefore the degree of filling of an APF part can be influenced in a targeted manner because the distance between the droplets is changed. The higher the form factor, the greater the distance between the droplets. In the

case of certain soft materials such as thermoplastic elastomer (TPE) for example, it is even possible to vary the Shore hardness of the part manufactured by changing the aspect ratio (Fig. 4). Accordingly, the mechanical part properties also change (Fig. 5).

The example of polished test plates made from PMMA (type: Plexiglas 7N) also shows how a transparency of the parts can be achieved by using special process parameters. In this case, the droplets are extremely densely packed and the test plate was polished after the building process (Fig. 6).

### Industrial Functional Parts Made from Original Materials

In terms of industries and areas of application, the APF process has virtually little limits. With its open system the Freeformer is currently finding its way into industrial applications: Functional plastic parts can be cost-effectively manufactured individually or in small volumes to speed up the transition to high-volume parts and, accordingly, to market. Individualization of high-volume products, e.g., through an additive imprinted lettering, means that plastic parts can be enhanced in such a way as to generate added value for manufacturers.

The Freeformer is not only suitable for prototyping, but above all for the industrial additive manufacturing of functional parts. One example is air ducts. A Freeformer produced this 8.5-gram parts from a PC (Lexan 940) approved for aerospace applications (Fig. 7). Using PP (Braskem CP 393) and the support material Armat 12, which is later dissolved in a water bath, functional cable clips with technical snap hooks can be produced with delicate and durable structures of which feature a "click effect" (Fig. 8).

With the Freeformer, the company Iigus primarily processes its own tribological materials. Corrosion and abrasion-resistant sliding bearings made from iglidur J260, which has sliding properties without requiring external lubricants, are produced for example. In the test laboratory, they have been found to be as wear-resistant as injection molded parts made of the same material.

### Two-Component Parts

Because the Freeformer is equipped with two discharge units as standard, the second unit can be used for an additional component in order to, for example, produce a part in various colors, with special tactile qualities, with integrated functions or as a hard/soft combination. Complex



geometries can also be achieved with the aid of support structures. In developing new support materials for the APF process, Arburg collaborates with universities and established material partners and also uses their expertise in compounding. Water-soluble Armat 11 and Armat 12 are available especially for processing PP. With Armat 21, an alkaline-soluble material is also obtainable.

In the APF process, parts can be built and manufactured without the technical production restrictions familiar from injection molding. With the aid of support materials, which can be washed away after the freeforming process, even complex component groups can be produced in ready-assembled form such as articulated rope pulleys (Fig. 9).

The rope pulley was built including housing and fastening hook and is movable via joints. Its geometry was optimized, taking into account the force application and tension characteristic and tested via tension tests. Weighing 61.5 g, the additively manufactured part made of a chemically resistant bio-polyamide (Grilamid XE4010) has a load-bearing capacity of 100 kg and therefore is also interesting with regard to the topic of lightweight construction.

Taking into account certain production restrictions and the self-supporting angle, even moving planetary rollers made from the hard/soft combination TPU and PHA (Arboblend) can be produced without use of a support material (Title figure).

### Customized Individual Parts and Functional Materials

For industrial applications, customized plastic parts are ideally suited for consumer goods and one-off medical parts. As examples, the Freeformer has already produced sawing templates from PA, which are used as individualized surgical aids, as well as implants such as skull, cheek and finger bones made from medical PLLA (e.g. Purasorb PL18 or Resomer LR 708), which dissolve in the body after a specified time (Fig. 10).

The benefits of additive manufacturing also include the ability to produce small batches on-site in line with day-to-day requirements. This saves additional logistics costs and time. Spare parts and equipment such as assembly devices and



**Fig. 6.** If the droplets are extremely densely packed, transparent test plates made from PMMA can be manufactured using the APF process (© Arburg)



**Fig. 7.** Air ducts from a specially approved PC for aerospace applications, e.g., for installation over passenger seats in airplane (© Arburg)



**Fig. 8.** Additively manufactured cable clips made from semi-crystalline standard PP are characterized by delicate structures and the click effect typical of injection molded parts (© Arburg)



**Fig. 9.** Complete module additively manufactured in a fully assembled state: an articulated rope pulley made from bio-PA has a load-bearing capacity of 100 kg (© Arburg)

grippers for automation solutions can, for example, be produced quickly, flexibly and inexpensively according to requirements (Fig. 11).

With functional materials, additional properties can be integrated into parts in a targeted manner. In the case of the "light sticks" manufactured additively using the Freeformer by the Fraunhofer ICT, electrically conductive Carbon Nanotubes (CNTs), for example, are compounded into a PC+ABS blend so that an inserted LED lights up when a

current is applied (*Kunststoffe international* 5/2018, p. 15).

### Cost-Effective Production of Small Volume Batches

One frequently asked question relates to the cost-effectiveness of additive part manufacturing. A costing example for in-house Arburg production shows the threshold from which it makes sense to use additive manufacturing instead of injection molding (Fig. 12). The part con- ➤

**Fig. 10.** By way of example, a Freeformer produced an individually adapted cranial bone implant made from medical grade PLLA granulate (© Arburg)



**Fig. 11.** Interesting applications for the APF process are two-component gripper fingers made from PA and TPE (© Arburg)

cerned is a 0.09g spacer made from PEI for installation in the electrical connectors of Allrounders. The annual parts requirement is around 1200. The Freeformer additively manufactures a small-volume batch of 70 parts in a build time of around three hours.

An injection molding machine produces four of these parts in eight seconds – the entire annual production can thus be met in only 40 min. However, an appropriate mold is necessary, the cost of which amounts to around EUR 8000. In this case, break-even would only be reached at a unit volume of 5540. With overhead costs of EUR 1792, the cost for the 1200 spacers required is many times lower with the APF process, plus savings can be achieved in terms of warehousing. For cost-effective production, it is necessary to calculate precisely what part quantities are required in what time and which other financially relevant conditions need to be met.

### *Integrating Customer Requirements into Added Value and Freeformer in the Process Chain*

Above and beyond the additive manufacture of one-off parts and small-volume batches, high-volume parts can also be enhanced and customer wishes incorporated directly in the added value chain by combining additive manufacturing, injection molding and Industry 4.0 technologies. Just how the customer-specific individualization of high-volume parts can be achieved was first demonstrated by Arburg at the Hannover Messe 2015 using the example of a rocker-type light switch from Gira. At the K2016 and the Hannover Messe 2017, the IT-networked, spatially distributed production of “smart” luggage tags was shown (*Kunststoffe international 11/2016*, p.6).

One of the first Arburg customers to individualize products as single unit batches according to customer requirements is the Lego Group. A pilot project

was conducted in the summer of 2017 at the Lego Brand Retail store in Orlando, Florida/USA. Consumers were able to have key fobs with standard 4x2 bricks decorated with lettering or their own name “on demand” and to take their very own, unique part home with them (**Fig. 13**). The Freeformer can also be automated with a mobile Kuka seven-axis “iiwa” robot, as shown at Fakuma 2016 trade fair for the first time. For this purpose it was equipped with a Euromap 67 interface via which it communicated with the robotic system. The hood opened and closed fully automatically and the part carrier was also adapted (**Fig. 14**).

### *Conclusion*

Arburg Plastic Freeforming (APF) with the Freeformer is an open system designed for industrial additive manufacturing. The

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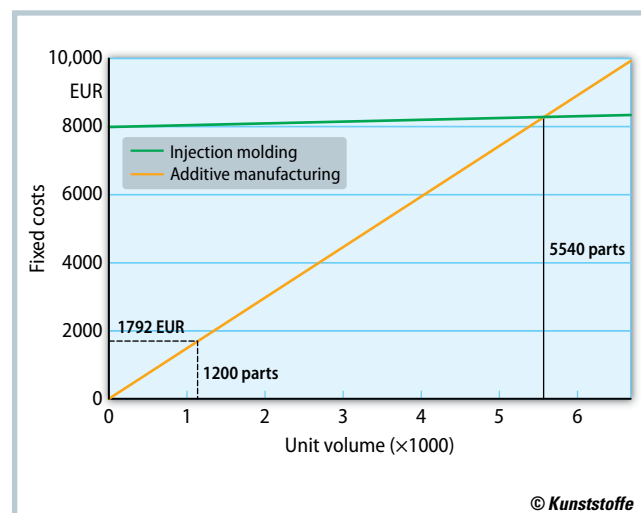
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**Fig. 12.** The APF process is the more cost-effective alternative for the 1200 spacers installed in Arburg injection molding machines annually. The break-even point for injection molding is a unit volume of 5540. Depending on part size and geometry, the break-even point shifts (source: Arburg)



**Fig. 13.** During the pilot project conducted at a Lego Store, consumers were able to have individualized key fobs produced with the aid of the Freeformer (© Arburg)



**Fig. 14.** In a fully IT-networked and comprehensively automated production line for individualized high-volume parts, a seven-axis robotic system is used to feed the build chamber of the Freeformer (© Arburg)

droplet size and process control can be adapted to the relevant requirements. This results in material-specific adjustment options comparable to those in injection molding. Which of these two processes is more cost-effective depends on the unit costs and must be assessed on a case-to-case basis.

Optimization of the machine and slicing parameters contributes significantly towards improving part quality. Trials and mechanical tensile tests have shown that, depending on the material, part densities and tensile strengths can be achieved which are close to those of injection molded parts using the APF

process through adapted process control. Functional parts made from original materials, can therefore be produced cost-effectively as one-off items or small-volume batches. Moreover, the Freeformer can be integrated in production lines, for example to individualize high-volume parts. ■