Perspectives on extrusion-based metal Additive Manufacturing: From bionic design to hollow structures and foams

Not so many years ago, the idea of taking a Powder Injection Moulding feedstock and adapting it to create filaments for use in an extrusion-based Additive Manufacturing machine would have sounded far-fetched. Today, however, a variety of sophisticated systems are available, along with metal and ceramic filaments from a range of manufacturers. Here, Dr Uwe Lohse, from XERION BERLIN LABORATORIES GmbH, considers how the unique combination of feedstock extrusion and sintering presents a range of component design concepts that enable previously impossible forms and functions.

Additive Manufacturing is penetrating ever further into numerous areas of industry. While it has already become widely used in plastics, other materials – not only metal and ceramics, but also construction materials and biological tissues – are becoming hotspots for further development.

With metals in particular, it is vital to ensure that additively manufactured components do not differ in any essential parameters from conventionally produced ones. Thus, in nearly all applications, a component density of > 99% of the theoretical value is desired, i.e. a density equivalent to the parameters achieved in wrought metallurgy, or that are possible in Metal Injection Moulding (MIM) when combined with a post-processing step such as Hot Isostatic Pressing (HIP). Likewise, the surface quality of metal AM parts must be comparable with that achieved by subtractive processes such as turning, milling or grinding. In most cases, a post-processing step such as polishing is obligatory.

This article presents an overview of some of the design opportunities presented by Material Extrusion (MEX), also known as Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM). From the incorporation of 'bionic' design principles to the use of hollow cavities, it is now possible to design and manufacture highly sophisticated components using MEX in far greater quantities than before and to tailor them to a far greater extent to a particular use.

When it comes to the application of bionic nature-inspired design principles, the concept is not to directly adopt natural structures

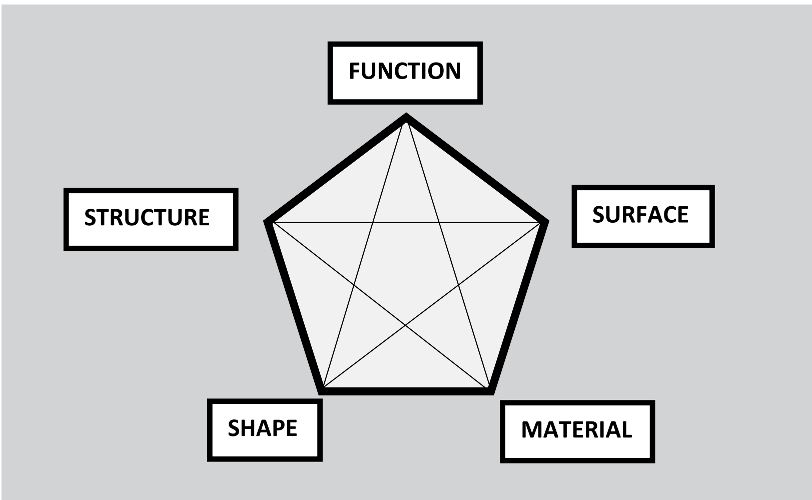

Fig. 1 To achieve the desired characteristics for metal AM parts, five major properties of the component to be manufactured need to be determined

within a technical application [1], but about looking for analogies and inspiration from the natural world in order to improve a component's performance and effectiveness. In this respect, the application of bionic principles to metallic components is justified. In biological structures, the tendency to minimise the metabolic energy required for growth is omnipresent. Closely related with this is a strict drive towards low-mass construction, meaning that many parallels with lightweight component design are apparent.

To achieve the desired characteristics for metal AM parts, five key component properties need to be determined. This pentagon of properties is shown schematically in Fig. 1 and will be further explained below.

The MEX of metallic and ceramic components is well on its way to becoming an established process and, as with all processes, it has advantages and disadvantages. The process is particularly suitable for nature-inspired methods of manufacture as it allows extensive freedom in the choice of material and the design of the part's interior, such as internal features like hollow spaces or channels within the part.

After a part has been built by MEX using one of the many systems available on the market – some of which are 'open platform' to deploy filaments from various manufacturers [2, 3] – a debinding and sintering stage is required. During this process parts will shrink by up to 20% by volume.

Material	Sintering temperature	Sintering atmosphere	Source
316L stainless steel (1.4435)	1,340–1,390°C	Hydrogen	[4,5]
17-4 PH stainless steel (1.4542)	1,320–1,370°C	Hydrogen	[4]
42CrMo4 heat treatable steel (1.7225)	1,300–1,330°C	Nitrogen	[5]
Titanium Ti6Al4V (3.7165)	1,100–1,400°C	High-vacuum	[4]
Alumina (Al_2O_3)	1,475–1,650°C	Air	[4,6,7]
Zirconia (ZrO_2)	1,450–1,500°C	Air	[4,6,7]
Silicon carbide (SiC)	2,100–2,200°C	Argon	[6]

Table 1 A selection of metal and ceramic materials currently available for MEX

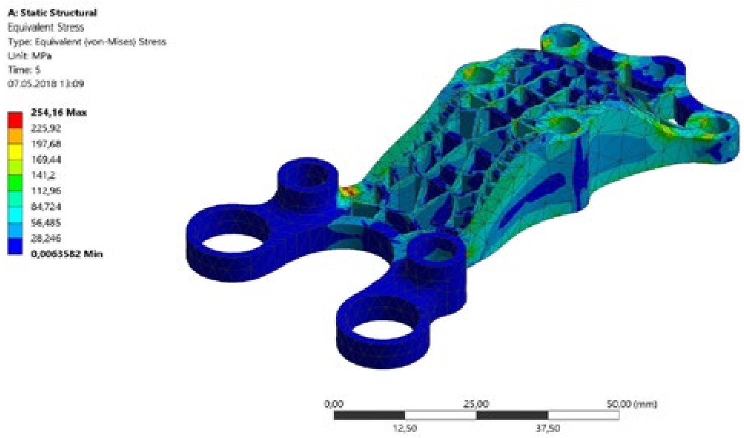

Fig. 2 Calculation of the von Mises stress in a 'bionically inspired' supporting element

Materials for MEX

One of the advantages of extrusion-based Additive Manufacturing is the wide variety of materials that can be processed. In principle, it is possible to extrude a whole range of metal and ceramic powders. These have to be mixed with the right proportion of binders and shaped into filaments that can then be processed by MEX. Another decisive advantage is the complete use of the powder within the filament; 100% of the powder input into the process makes up the finished component, in contrast to powder bed processes such as Powder Bed Fusion (PBF) and Binder Jetting (BJT) where only selected parts of a layer of powder are used to form the final part. Table 1 shows a selection of materials that are currently available as filaments.

From this broad palette of metallic and ceramic materials, the intended application will inevitably drive material choice. Because of the various atmospheres required by these materials, sintering is best achieved using a multi-atmosphere sintering furnace. This makes it possible to process a range of materials for research or small series production [2].

Multi-material components

The manufacture of multi-material components can be achieved using MEX machines with two or more filament extrusion nozzles. The join between the two materials can be designed with relative freedom and does not have to run along a fixed plane, as is required in other processes. For multi-material component sintering, at least four of the physical parameters of the materials used must lie within the same ranges:

- Sintering temperature
- Sintering atmosphere
- Shrinkage
- Coefficient of thermal expansion

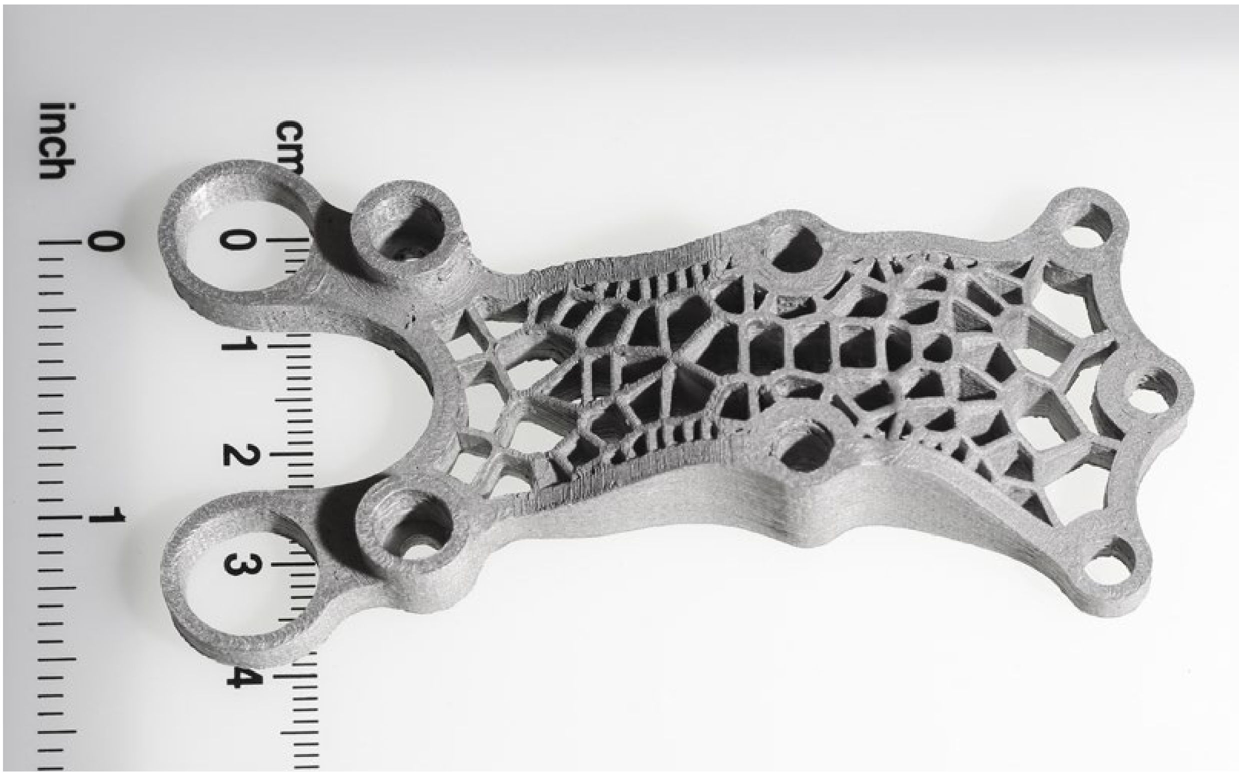

Fig. 3 Supporting element manufactured by MEX in 17-4 PH stainless steel after debinding and sintering

These are challenging requirements, which is, in part, why such components cannot yet be manufactured on an industrial scale.

Unique part design opportunities

Because AM is a toolless manufacturing process, a wide degree of freedom is possible in designing the external shape of components. This freedom is already being used extensively, with a long list of example applications. As a rule, the shapes developed can often combine nature-inspired design principles with conventional approaches to lightweight construction. It is to be expected that components in such shapes will find ever wider use. In certain cases, they go against our habitual expectations for what a robust mechanical component looks like; for this reason, it is not only technical considerations that play a role in the use of these bionically inspired forms.

Internal spaces and cavities
A great advantage of MEX, in contrast to PBF, is the ability to manufacture closed hollow cavities. From this, it is also evident that it is extremely well suited to imitating the hollow or porous structures found in nature. Often, these can be achieved without the use of support structures. This results in an extensive range of possibilities for determining the 'macroporosity' of components using filament-based processes.

To build hollow spaces within a component, the lower limit is one or two times the diameter of nozzle used, from 0.5–1.0 mm. The creation of such cavities, or macroporosity, is achieved in the build process itself and can thus be locally differentiated.

Microporosity as an opportunity
The sintering process can offer some interesting opportunities. Initially, sintering is perceived as a disadvantage by those new to the various metal AM processing routes, with the impression that it 'complicates' the manufacturing process chain. However, what some see as a disadvantage can be turned into an advantage, with an example being managing sintering parameters to control microporosity.

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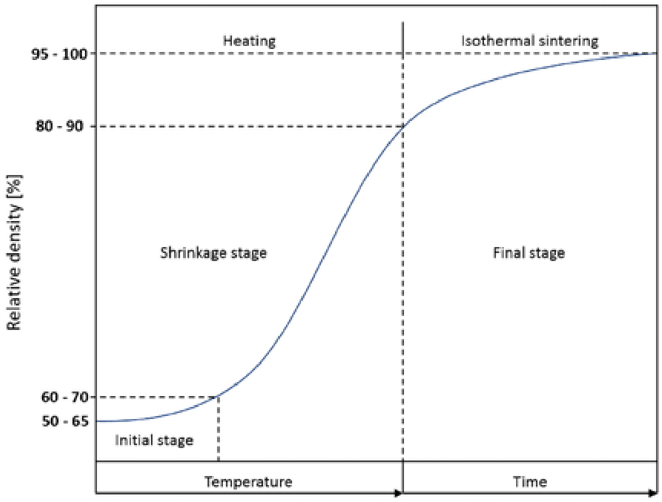

Fig. 4 Density changes during sintering (schematic) [8]

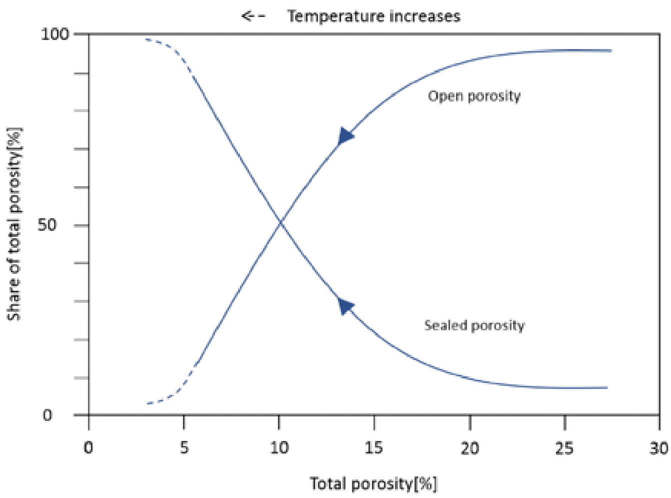

Fig. 5 Changes in open and closed porosity during sintering (schematic) [8]

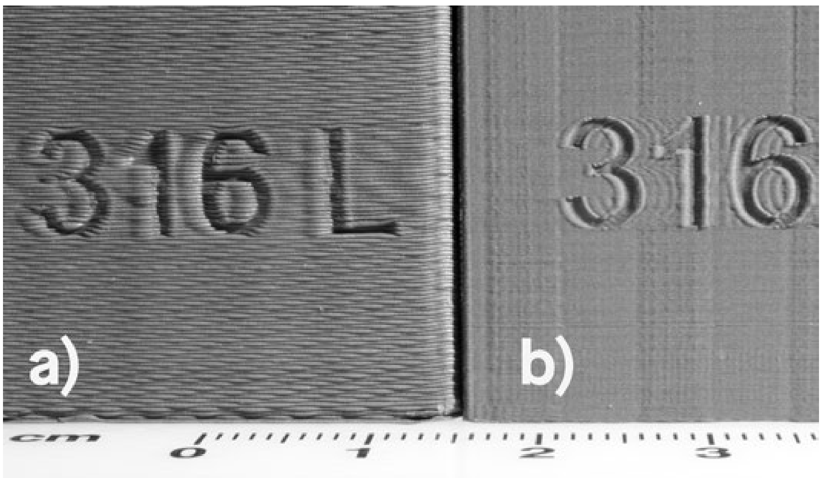

Fig. 6 Surface structure comparison of components built using a) a nozzle diameter of 0.8 mm and layer height of 0.25 mm, and b) a nozzle diameter of 0.4 mm and layer height of 0.05 mm

Here, sintering temperature and heating rate are the key parameters. If the sintering temperature is lowered, the sintering process will be 'incomplete' and the density of the component reduced. This can be advantageous, for example, for increasing the resistance to temperature changes of ceramics used in thermal applications. Naturally, this modification applies globally to the entire component. Fig. 4 shows how density is affected by sintering time and temperature and Fig. 5 shows the changes between open and close porosity during sintering.

There is particular potential here for the development of binder materials that can enable adjustments to post-sintered porosity or can be processed without shrinkage [9]. For this reason, in contrast to the routines developed so far, sinter-based Additive Manufacturing requires and makes it possible for completely new paths to be discovered. Only in this way can the full potential of this innovative manufacturing method be fully exploited.

Surface considerations

The design of surface structures is subject to relatively narrow tolerances. It is in the nature of all metal Additive Manufacturing processes that, to a greater or lesser extent, a rough surface results. This is particularly apparent in comparison with MIM, where the use of a highly-polished mould and the selection of finer powders can deliver extremely smooth surfaces.

With MEX, the structure of the surface can, to some extent, be managed. This can happen in two different ways. The first option is to set the build parameters in this area: for example, layer height, level of extrusion or speed of extrusion. The second option is to use multiple nozzle widths. For this, machines with two or four nozzle systems could be used. The use of a fine nozzle (e.g. with diameter of 0.4 mm) on the surface leads to a fine structure. For certain applications, of course, a coarser surface may be desirable, such as to make the surfaces of control elements non-slip.

Fig. 6 shows two different surface structures built using machines with a nozzle diameter of 0.8 mm and layer height of 0.25 mm and a nozzle diameter of 0.4 mm and layer height of 0.05 mm. The respective build times were 30 and 150 minutes.

To build infill structures, a much larger nozzle diameter can be used to speed up the process. Of course, there is also the option of using a surface made of a different material altogether, as described earlier in this article.

Functions that lead to applications

Hydraulic and pneumatic functions
The flow of fluids within structures is a well understood geological and biological principle. This is why it has been applied in the Additive Manufacturing of bionically inspired components from the very beginning. What can now be regarded as a 'classic' example of this is the production of cooling or flow channels close to the surface of a part, something traditional manufacturing processes can only achieve with enormous effort (Fig. 7). The MEX route is also well suited for this, even if it does have drawbacks when compared with binder jet Additive Manufacturing processes.

Electrical functions
The integration of electrical conductors in non-conductive matrices opens up huge possibilities; this principle is also inspired by the natural world. The MEX process is well suited for this, as it is intrinsically easy to build two different materials in parallel using extrusion-based processes. One approach is to combine 17-4 PH stainless steel as the conductor with zirconium oxide as the ceramic matrix [10]; this combination fulfils the requirements given earlier in this article for material pairings with the same sintering parameters. However, the stainless steel used is unsuitable as a heating element material for temperatures above 1,000°C. For this reason, rather than using 'pure' metal and ceramic materials for both components, filaments containing a blend of metal-ceramic mixtures can be used with gradual differentiation between each other. Combinations of tantalum and niobium are currently being tested [9].

Fig. 7 Ring shower head with interior water channel and various nozzle exit angles (Courtesy Aloys F Dornbracht GmbH & Co. KG)

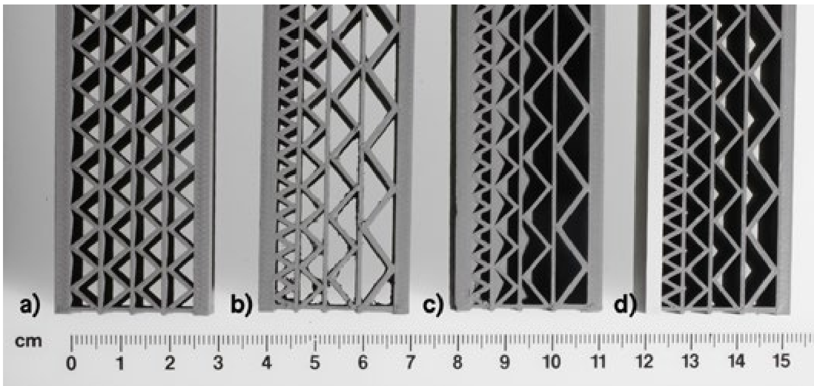

Fig. 8 Component evolution through design of hollow spaces and material selection, showing a) evenly distributed cavities, b) cavities whose size decreases from top to bottom, c) a variant with closed inner spaces, and d) a gradation in cavity size with a surface made of a different material, in this case aluminium oxide ceramic

Combining MEX's advantages
The MEX process allows a broad spectrum of options in designing components, as per the pentagon of properties outlined earlier. Fig. 8 shows the four-stage evolution of a 17-4 PH stainless steel component design produced by MEX. In a) the cavities are evenly distributed, while in b) their size increases from the left. Both a) and b) have open cavities, while c) shows a variant with closed inner cavities. In variant d), alongside the gradation in cavity size, the surface is made of a different material, in this case an alumina oxide ceramic.

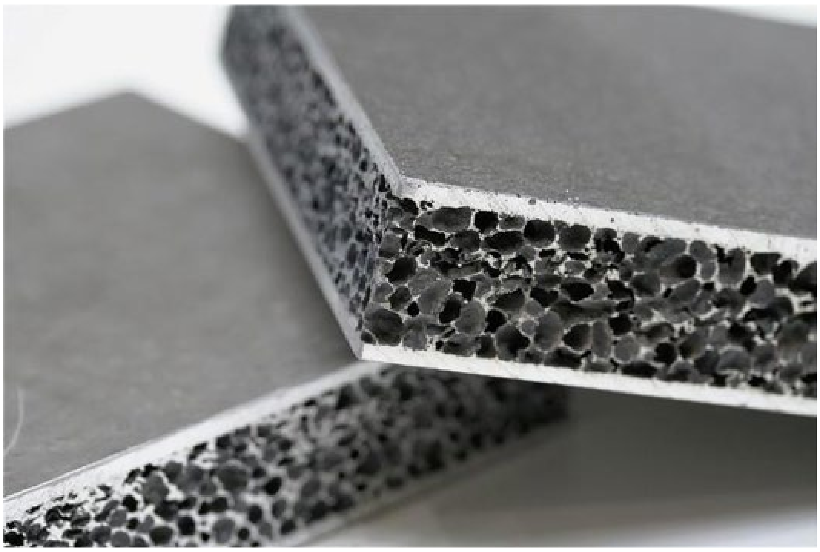

Fig. 9 Conventional closed-pore aluminium foam in a sandwich construction (Courtesy Fraunhofer IWU, Metallschaumzentrum Chemnitz)

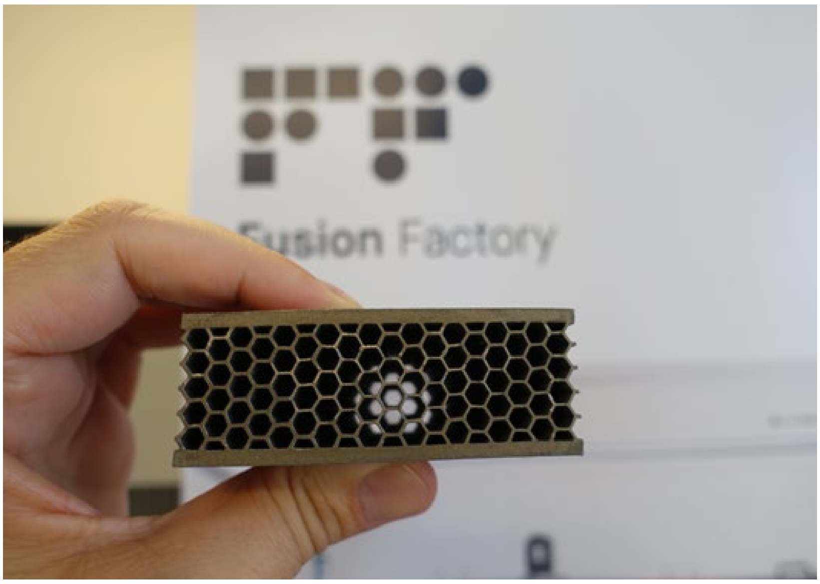

Fig. 10 Additively manufactured sandwich plate in stainless steel (Courtesy XERION)

MEX metal foams: combining open and closed porosity in one component

Metal foams are enjoying increased interest thanks to their range of applications, from use in industrial machines and automotive design to ballistic protection. Conventional manufacturing processes lead either to closed-pore or open-pore foams. A combination of both types is only possible through joining at a later stage. For this reason, the MEX process is particularly useful as it allows the free but defined distribution of cavities or hollow spaces in the component. The closed areas can be clearly separated from those that allow through-flow and it is also very easy to integrate channels for liquid and gas entry into the component.

Outlook

Additive Manufacturing is far more than a new addition to the list of manufacturing technologies. On a far greater scale than previously possible, it allows the nature-inspired design of components. The type and means of manufacture almost inevitably leads to an organic approach. However, it is not to be ruled out that the inspiration may run in the opposite direction, with anthropogenic construction principles discovered at a later point in geological or organic structures. This occurred in spectacular fashion in the work of the visionary architect and mathematician R Buckminster Fuller [11]. It is to be expected that the various AM processes will change component design to a significant extent and this change will enormously increase the efficiency and ergonomic behaviour of human-made objects. To this end, it is necessary to 'cast off the shackles' of traditional habits of thought and perception and use the comprehensive possibilities of Additive Manufacturing to the fullest.

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